Designing acute physical activity for children's cognition: Effects of cognitive challenge, bout duration, and positive feedback

Inauguraldissertation

der Philosophisch-humanwissenschaftlichen Fakultät der Universität Bern

zur Erlangung der Doktorwürde

vorgelegt von

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Originaldokument gespeichert auf dem Webserver der Universitätsbibliothek Bern

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source: https://doi.org/10.48549/6333 | downloaded: 9.1.2026

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Von der Philosophisch-humanwissenschaftlichen Fakultät der Universität Bern auf Antrag von

Prof. Dr. Mirko Schmidt (Hauptgutachter), Dr. Valentin Benzing (Zweitgutachter) und Prof. Dr. Claudia Voelcker-Rehage (Drittgutachterin) angenommen.

Bern, den 9. August 2023

Der Dekan: Prof. Dr. Elmar Anhalt

To my parents, Caterina and Joachim,

who raised us with loving hearts and genuine curiosity

The cumulative dissertation includes the following publications:

I

Anzeneder, **S.**, Zehnder, C., Martin-Niedecken, A. L., Schmidt, M., & Benzing, V. (2023). Acute exercise and children's cognitive functioning: What is the optimal dose of cognitive challenge? *Psychology of Sport and Exercise, 66*, 102404. https://doi.org/10.1016/j.psychsport.2023.102404

II

Anzeneder, **S.**, Zehnder, C., Schmid, J., Martin-Niedecken, A. L., Schmidt, M., & Benzing, V. (2023). Dose-response relation between the duration of a cognitively challenging bout of physical exercise and children's cognition. *Scandinavian Journal of Medicine & Science in Sports*, *33*(8), 1439-51. https://doi.org/10.1111/sms.14370

III

Anzeneder, **S.**, Schmid, J., Zehnder, C., Koch, L., Martin-Niedecken, A. L., Schmidt, M., & Benzing, V. (2024). Acute cognitively challenging exercise as "cognitive booster" for children: Positive feedback matters! *Mental Health and Physical Activity, 27*, 100621. https://doi.org/10.1016/j.mhpa.2024.100621

Further publications that were not included in this dissertation:

Benzing, V., Siegwart, V., **Anzeneder, S.**, Spitzhüttl, J., Grotzer, M., Roebers, C. M., Steinlin, M., Leibundgut, K., Everts, R., & Schmidt, M. (2022). The mediational role of executive functions for the relationship between motor ability and academic performance in pediatric cancer survivors. *Psychology of Sport & Exercise, 60*, 102160. https://doi.org/10.1016/j.psychsport.2022.102160

Pesce, C., Vazou, S., Benzing, V., Alvarez-Bueno, C., **Anzeneder, S.**, Mavilidi, M., Leone, L., & Schmidt, M. (2021). Effects of chronic physical activity on cognition across the lifespan: A systematic meta-review of randomized controlled trials and realist synthesis of contextualized mechanisms. *International Review of Sport and Exercise Psychology*, 1-39. http://doi.org/10.1080/1750984X.2021.1929404

Schmidt, M., Egger, F., **Anzeneder, S.**, & Benzing, V. (2021). Acute cognitively challenging physical activity to promote children's cognition. In R. Bailey, J. P. Agans, J. Côté, A. Daly-Smith, & P. D. Tomporowski (Eds.), *Physical activity and sport during the first ten years of life* (pp.141-155). Routledge. https://doi.org/10.4324/9780429352645

Umbrella paper

Designing acute physical activity for children's cognition: Effects of cognitive challenge, bout duration, and positive feedback

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Abstract

Acute physical activity (PA) transiently enhances children's cognition. However, heterogeneous effect sizes necessitate investigating potential moderators that constrain PA effects on cognition. Thus, the overall aim of the research project was to investigate dose-response relationships between qualitative and quantitative task characteristics of acute cognitively challenging bouts of PA as well as the influence of contextual factors such as the delivery style to orient the design of school-based active breaks beneficial for cognition.

The present dissertation incorporates findings from three studies aimed at systematically investigating: The influence of the cognitive challenge level on children's cognition (*study I*); the optimal duration of the identified cognitive challenge level to maximize benefits (*study II*); the role of feedback and related affective states in the PA-cognition relationship (*study III*).

Overall, the present findings were in line with theoretical assumptions. Compared to less challenging bouts, acute PA with high-challenging content benefitted children's executive control the most (*study I*). Bout duration influenced information processing speed, with best performances after a 15 min bout (*study II*). A delivery style combining music with positive feedback created favorable conditions for improving executive control and inducing positive affective states, even though affective states did not mediate feedback effects (*study III*). Individual characteristics moderated the effects of cognitive challenge and duration.

Results emphasize the importance of considering the interplay of different task characteristics and contextual factors to generate optimal, individualized stimulation for children's cognition. This is of great practical importance in educational settings to design active breaks that enhance cognitive functions essential for learning and create enjoyable experiences that lay the foundation for an active lifestyle. More research is needed to explore how cognitively challenging active breaks can be designed and implemented in the school context.

Content

A societal and scientific problem

The significance of movement for children's healthy development is widely acknowledged in the fields of science, education, and politics. Compelling evidence highlights that regular physical activity (PA) improves children's physical (Poitras et al., 2016) and mental health (Biddle et al., 2019; Lubans et al., 2016). Nonetheless, secular trends mostly point on a decline in children's PA levels associated with an increase in sedentariness (van Stralen et al., 2014). The reduction of children's PA levels is not only alarming in terms of their health but also in terms of their cognitive development, knowing that both motor and cognitive abilities are strongly interrelated (Diamond, 2000; Stodden et al., 2023), and together predict academic achievement (Schmidt et al., 2017).

Schools are key settings to promote large-scale quality PA aimed to capitalize on its enjoyable nature and beneficial effect on cognitive functions (Vazou & Smiley-Oyen, 2014). Consequently, many school-based PA programs in form of PA breaks, consisting of short bouts of PA between academic learning phases, or physically active learning, incorporating PA during academic lessons, have been developed, implemented, and evaluated (e.g., Mavilidi et al., 2022). While these programs are often designed based on practical considerations rather than theoretical foundations, the advocacy for PA is increasingly supported by evidence-based recommendations highlighting positive PA effects on cognitive functions relevant to learning and academic achievement (Howie & Pate, 2012). However, time constraints and educational priorities often hinder the implementation of additional PA opportunities during the school routine (Leone & Pesce, 2017).

A scientific issue is intertwined with these societal and educational concerns. Even if the developing body of evidence is strong enough to support the conclusion that PA does not interfere with or take away time from learning (Singh et al., 2019), it is still debated how PA interventions should be designed to reap the largest benefits on cognitive functions relevant to learning and academic achievement (Diamond & Ling, 2016, 2019; Hillman et al., 2019). Discrepancies in conclusions across evidence syntheses of both long-term (i.e., chronic PA) and short-term effects (i.e., acute bouts of PA) are paralleled by considerable heterogeneity in effect sizes across primary studies (Lubans et al., 2022). This heterogeneity implies the presence of moderators that complexify the pattern of PA effects on cognitive performance and delimit the generalizability of study results.

One moderator that has attracted increasing interest in recent years is the cognitive challenge (demand) inherent in movement tasks. Cognitive challenge generates cognitive engagement, which, in turn, appears to be beneficial for learning relevant functions such as executive functions (EFs; Best, 2010; Pesce, 2012; Tomporowski et al., 2015). Whereas chronic cognitively challenging PA seems to benefit children's EFs in the long-term (e.g., Álvarez-Bueno et al., 2017; Vazou et al., 2019), as regards transient effects after a single cognitively challenging bout of PA, results are inconsistent and general conclusions are limited by differences across studies (Paschen et al., 2019; Schmidt et al., 2021).

As indicated by an expert panel, further experimental research into possible moderators of the PA-cognition relationship also considering underlying mechanisms is needed (Singh et al., 2019). Following this call, the overarching aim of the publications included in this dissertation was to investigate dose-response relationships between task characteristics of acute cognitively challenging bouts of PA, while also considering the influence of contextual factors, to orient the design of school-based active breaks beneficial for cognitive functions. Specifically, a series of three studies aimed to: Shed light on which cognitive challenge level in acute PA impacts children's cognitive performance (*study I*); investigate which bout duration of the identified optimal cognitive challenge level is necessary to reap the largest benefits (*study II*); and manipulate feedback forms during cognitively challenging bouts of PA to elucidate the role of the delivery style and related affective states in the PA-cognition relationship (*study III*).

The umbrella paper presents key research concepts related to PA and cognition, describes previous empirical evidence within theoretical frameworks, discusses the main findings of the three studies, and offers insights for future research and recommendations for implementation in school practice.

Definition of terms

Physical activity and exercise

The term "physical activity" (PA) is defined as any bodily movement that involves energy expenditure through skeletal muscles (Caspersen et al., 1985). Within this broader term, "exercise" is considered a subset of PA that is planned, structured, and repetitive, with the aim of maintaining or improving outcomes in different domains, such as physical and cognitive (Herold et al., 2021). In PA and cognition research, the prevalent use of the term "exercise" was progressively extended toward the umbrella term "PA" to encompass a broader range of PA spanning from highly structured to unstructured activities and provide a conceptually more appropriate descriptor for the existing literature (Pontifex et al., 2019). PA interventions are *chronic* when focusing on long-term effects elicited by continuative practice over a prolonged time (weeks to years). They are *acute* when focusing on transient effects of a single bout of PA.

Cognitively challenging physical activity

A further distinction can be made between more energetically determined PA, such as aerobic or strength-enhancing PA, and more information-oriented activities, such as coordinative or dual-task PA. Energetically determined activities are characterized by high metabolic and low cognitive demands, while more information-oriented activities combine both high neuromuscular and cognitive demands (Lämmle et al., 2010). Besides these aspects, the described activities generally go along with a certain degree to which movements are automatized. For example, whilst running on a treadmill can be performed highly automatically for most healthy children, learning a dance sequence requires a higher level of cognitive control processes. Moreover, as pointed out by Pesce (2012), the degree of automatization depends not only on the metabolic or neuromuscular demands of an activity but also on its complexity. Task complexity is interactively determined by task and task performer characteristics (Campbell, 1988). Thus, the performer's prior knowledge, experience, developmental stage, and skill level influence the difficulty of the task and the amount of cognitive control processes involved. Building upon the definition of cognitive engagement proposed by Tomporowski and colleagues (2015), *cognitively challenging PA* is any PA that generates cognitive engagement, requiring individuals to allocate attentional resources and exhibit substantial cognitive effort to master the task (e.g., coordinative PA, team-games, PA with dual-task demands). Cognitive demands can be additional, where resolving a cognitive task is not necessary to successfully complete the motor-cognitive task (e.g., stationary cycling while citing alternate letters), or incorporated, where resolving a cognitive task is a prerequisite for successful completion of the motor-cognitive task (e.g., dancing; Herold et al., 2018).

Cognition, executive functions, and attention networks

The term "cognition" encompasses mental processes involved in acquiring, storing, retrieving, and processing information (Wessinger & Clapham, 2009). It includes both bottom-up (basic information processing) and top-down cognitive processes (control of thoughts, emotions, or behaviors). Among these top-down processes, executive functions (EFs) have gained increasing research interest. EFs are higher-level functions, associated with frontoparietal brain areas (especially prefrontal cortex) and the anterior cingulate, that are required for performing and monitoring goal-oriented, adaptive, and flexible behavior, particularly in complex and changing environments (Diamond, 2013, 2020; Miyake et al., 2000). As suggested by Miyake and colleagues (2000), and widely established in cognitive neuroscience research (Diamond, 2013, 2020), EFs can be divided into three core dimensions: Inhibition, working memory and cognitive flexibility. Inhibition involves avoiding dominant, automatic responses or resisting distractor interference. Working memory refers to the ability to hold and manipulate relevant information in short-term memory. Cognitive flexibility denotes the ability to switch between mental sets or tasks. While this three-factor structure has been repeatedly demonstrated in adults, a complete separation is difficult due to the interplay of core EFs in guiding behavior (Zink et al., 2021). In children, EFs emerge as a unitary process during infancy and gradually differentiate into multiple factors with increasing age (Brydges et al., 2014; Karr et al., 2018). As suggested by a recent re-analysis of latent variable studies (Karr et al., 2018), in school-aged children a three-factor model seems appropriate. Thus, it is recommended to measure core EFs separately to understand the developmental trajectories of each component (Roebers, 2017).

From an educational perspective, EFs are highly relevant due to their predictive validity for learning-related behaviors (Neuenschwander et al., 2012) and academic achievement (Viterbori et al., 2015). Inhibitory aspects of executive functioning play a crucial role in learning competencies, such as self-regulation (Liew, 2012). Among core EFs, inhibition is a multifaced component and its sub-dimension of interference control, also known executive control (Diamond, 2013, 2020), lies at the intersection point between EFs and attention.

Indeed, executive control is also one of three independent yet interacting attention networks, along with alerting and orienting (Petersen & Posner, 2012). Alerting ensures sensitivity to incoming stimuli and readiness to react. Orienting enables the selection of information by disengaging, shifting, and re-engaging attention in the visual space. Converging evidence confirms this differentiation, with each network involving distinct brain functions: Executive control has been associated with the activation in the anterior cingulate and lateral prefrontal cortex, alerting involves thalamic, frontal and parietal regions, orienting engages the parietal lobe, and frontal eye field (Fan et al., 2009; Petersen & Posner, 2012).

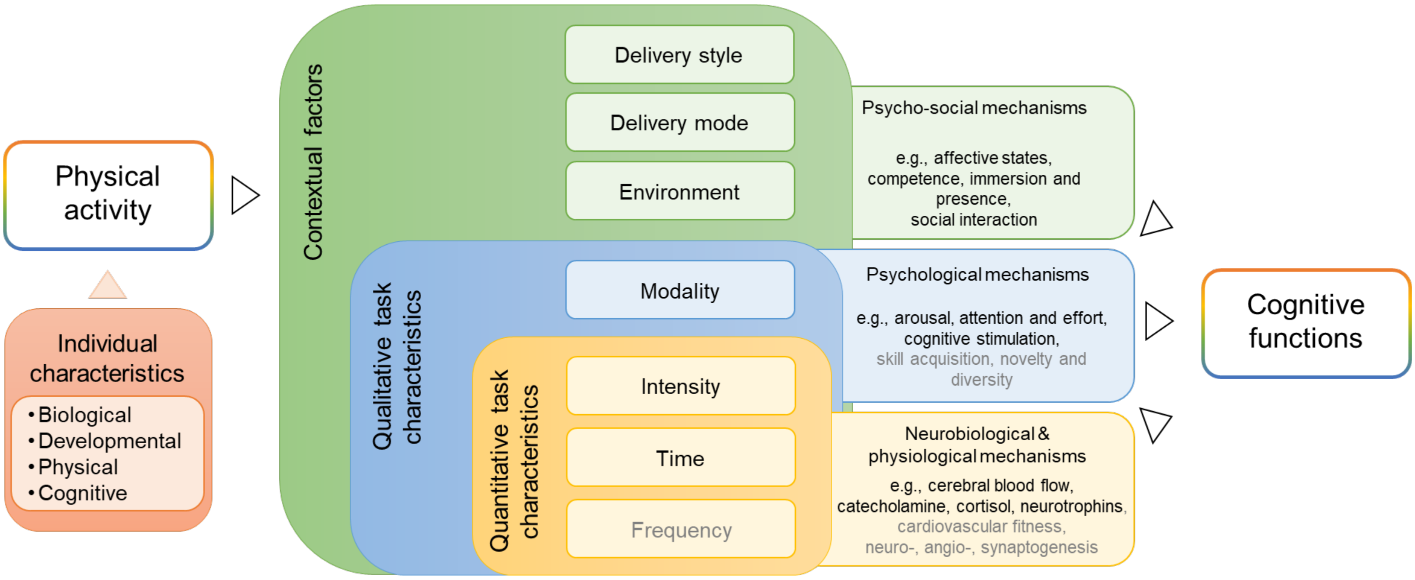
In PA and cognition research, executive control has predominantly been assessed using a Flanker Task (Eriksen & Eriksen, 1974) which measures pure reaction times (RTs) and response accuracy of interference effects. However, this task does not capture the interaction between executive control and other cognitive processes. From an ecological perspective, the interactive functioning of attention networks seems to better reflect cognitive and emotional control processes relevant to academic learning (Posner & Rothbart, 2014). These nuances can be addressed using the attention network paradigm (Petersen & Posner, 2012), which suggests that attention network systems interact to adapt information processing to environmental demands (Fan et al., 2009). Specifically, alerting improves the speed of executive control but negatively affects its accuracy. Valid orienting facilitates executive control and invalid orienting impairs it.

Theoretical background and empirical evidence

Over the last decade, a growing body of research has examined the link between PA and cognitive performance (Erickson et al., 2019; Pesce et al., 2021). A recurrent issue was whether, among cognitive functions, EFs are selectively more sensitive to PA interventions (e.g., Chang et al., 2012; Ludyga et al., 2020). This issue is particularly relevant for PA interventions with children and adolescents, due to the predictive validity of EFs for academic achievement (Diamond, 2013, 2020). PA effects on children's EFs have been synthesized by meta-analytical evidence with small to medium effects both in the long- (Álvarez-Bueno et al., 2017; de Greeff et al., 2018; Leahy et al., 2020; Li et al., 2020; Takacs & Kassai, 2019; Xue et al., 2019) and short-term (Moreau & Chou, 2019 ; de Greeff et al., 2018; Leahy et al., 2020; Ludyga et al., 2016; Verburgh et al., 2014). Among EFs sub-domains, chronic PA interventions seem to have a more general effect (executive control: ES from 0.17 to 0.37; working memory: ES from 0.10 to 0.36; cognitive flexibility: ES from -0.07 to 0.66; Álvarez-Bueno et al., 2017; de Greeff et al., 2018; Li et al., 2020; Takacs & Kassai, 2019; Xue et al., 2019), whereas acute PA shows selectively greater effects for executive control (with ES = 0.28 and 0.57; de Greeff et al., 2018; Verburgh et al., 2014). However, the high heterogeneity in effect sizes and the inconclusive pattern of long- (e.g., Singh et al., 2019) and short-term results (e.g., Hillman et al., 2019) have raised fundamental questions about the effectiveness of PA in enhancing cognitive functions (Ciria et al., 2023) and especially EFs (Furley et al., 2023).

Research increasingly considered possible moderators that constrain both long-term and transient PA effects (Lubans et al., 2022; Pesce et al., 2021). Besides selected cognitive outcomes (de Greeff et al., 2018; Pontifex et al., 2019) and comparison groups (Pontifex et al., 2019; Vazou et al., 2019), important moderators refer broadly to quantitative task characteristics (i.e., intensity, time, and frequency [the latter for chronic PA only]), qualitative task characteristics (i.e, modality such as cognitive complexity of the task; Lubans et al., 2022; Pesce, 2012), contextual factors (i.e., delivery style, delivery mode, and environment; Pesce et al., 2021; Vella et al., 2023), and individual characteristics (i.e., biological, developmental, physical and cognitive factors; Herold et al., 2021; Pesce, 2009; see Figure 1).

Figure 1. An integrated framework of moderators of PA effects on cognition and underlying mechanisms



Note. Gray text refers to chronic PA only.

Investigations into quantitative task characteristics tried to characterize dose-response relationships among different PA parameters and cognition (Erickson et al., 2019; Herold et al., 2019) and generally referred to neurobiological and physiological mechanisms contributing to cellular-molecular and structural-functional changes in the brain underlying cognitive performance (Stillman et al., 2016; Voss et al., 2013). Long-term cognitive benefits have been associated with the upregulation of neurotrophins (e.g., brain-derived neurotrophic factor; *neurotrophic stimulation hypothesis*) and enhanced processes of neuro-, angio- and synaptogenesis (Erickson et al., 2019; Stillman et al., 2016). It has been suggested that increased cardiovascular fitness caused by chronic PA mediates the relationship between PA and cognitive performance (i.e., *cardiovascular fitness hypothesis*; Hillman et al., 2019), even though meta-analytic syntheses lacked to confirm it (e.g., Etnier et al., 2006). Conversely, transient cognitive benefits have been associated with enhanced cerebral blood flow and lactate in the brain, enhanced levels of neurotrophic factors, release of catecholamine (e.g., dopamine, noradrenaline), and increased cortisol levels (McMorris, 2016; Piepmeier & Etnier, 2014). However, even though intriguing evidence suggests that some neurobiological changes supporting long-term structural brain development may also underlie transient cognitive benefits, the direct relationship between acute PA-induced brain changes and cognitive performance is still limited (Pontifex et al., 2019).

This range of neurobiological and physiological changes is thought to lead to altered states, such as increased arousal and activation, facilitating performance in subsequent cognitive tasks (i.e., *arousal theory*; Audiffren et al., 2009). Arousal refers to the readiness to process sensory and perceptual inputs, while activation is the motor readiness to respond. Within this theory, an inverted U-shaped function between PA characteristics and cognition has been hypothesized (Lambourne & Tomporowski, 2010), according to which cognitive performance is predicted to improve and peak as physiological arousal increases and then deteriorate as arousal levels approach maximal levels. Related to this issue, it is assumed that attentional resources are limited (i.e., *capacity theory of attention*; Kahneman, 1973) and a combination of arousal, activation, and cognitive effort (i.e., an evaluative component of arousal and activation) is crucial for energizing separate cognitive processing stages (i.e., *cognitive-energetic theory*; Sanders, 1983). All these hypotheses of underlying mechanisms have been proposed to explain dose-response relationships among quantitative task characteristics and cognitive performance. Evidence syntheses over the lifespan resulted in prescribing session durations of 60 min for long-term effects of chronic interventions of at least 22 weeks (Ludyga et al., 2020) and bouts of 11-20 min at moderate to vigorous intensity for transient cognitive benefits (Chang et al., 2012; McMorris & Hale, 2012).

However, investigations focusing solely on quantitative task characteristics may not be sufficient to characterize the complexity of the PA-cognition relationship. An interplay of neurobiological and psychological mechanisms may better explain PA effects on cognition (Pesce et al., 2021; Tomporowski & Pesce, 2019). Compelling evidence has shifted the focus from quantitative to qualitative task characteristics to explore whether PA effects on cognition may differ as a function of PA modality (i.e., cognitive complexity of the movement task; Pesce, 2012). As indicated by a recent comprehensive meta-regression of chronic PA studies over the lifespan (Ludyga et al., 2020), one of the most influential moderators of the PA-cognition relationship is PA modality, with coordinative, cognitively challenging, PA being most effective for improving cognitive functions compared to aerobic or resistance PA.

According to the *cognitive stimulation hypothesis*, cognitively challenging PA generates cognitive engagement. This latter is supposed to lead to better EF performance by pre-activating both transiently and in the long-term same brain regions that are used to control higher-order cognitive processes (Best, 2010; Pesce, 2012; Tomporowski et al., 2015), which are needed for performing subsequent EF tasks (Budde et al., 2008). This mechanism is further supported by the idea of common neural substrates in both complex cognitive and movement tasks: Combining cognitive and physical demands may produce synergistic effects due to co-activation and inter-connectedness of prefrontal cortex and cerebellum areas (Serrien et al., 2007). This neural co-activation is likely strongest when the task is novel, complex, and variable (Moreau & Conway, 2014). Combining the cognitive stimulation and cardiovascular fitness perspectives, it has also been suggested that cognitive enhancement following chronic PA is linked, independently from or interactively with the level of PA metabolic demands, to skill acquisition processes elicited by learning experiences in environments that are inherently rich in or purposefully enriched with cognitive challenges (i.e., *skill acquisition hypothesis*; Tomporowski & Pesce, 2019).

The above mentioned meta-analytical evidence over the lifespan (Ludyga et al., 2020) aligns with evidence syntheses of developmental studies suggesting that chronic cognitively challenging PA interventions have positive long-term effects on children's EFs (e.g., Álvarez-Bueno et al., 2017; Vazou et al., 2019). Instead, as regards transient effects after a single cognitively challenging bout of PA, results are inconsistent (Paschen et al., 2019; Schmidt et al., 2021; see Table 1). A closer examination of these studies reveals that inconsistencies could be explained by different combinations of quantitative and qualitative PA characteristics that interact with individual characteristics, as well as contextual factors such as delivery style, delivery mode and environment. Compared to less cognitively challenging bouts, some studies revealed positive effects in favor of more challenging conditions (see studies highlighted in green in Table 1), while others found no differences (see studies highlighted in yellow in Table 1), lower improvement or even detrimental effects (see studies highlighted in red in Table 1).

Table 1. Overview of acute cognitively challenging PA studies on EFs, differing in task characteristics, contextual factors, and individual characteristics

Authors	**Sample size**	**Age** [years *M* (*SD*)]	**Modality**	**Intensity** [HR *M* (*SD*)]	**Time** [min]	**Contextual factors**	**Affective states**	**EF outcomes**	**Results**
Benzing et al., 2016	65	14.5 (1.1)	Sedentary control (C) vs. exergame with low CE (ExL) vs. exergame with high CE (ExH)	C: 82.4 (19.2); ExL: 152.1 (27.1); ExH: 141.5 (23.3)	15	Unused classroom during school; virtual; individual	Covariates	Inhibition, flexibility	Fluency: ExH > ExL & C; ExL = C. Inhibition, shifting: no differences.
Budde et al., 2008	115	15.0 (1.2)	Normal sport lesson (NSL) vs. coordinative PA (COR)	NSL: 122.0 (27.1); COR: 122.3 (21.9)	10	PE during school; face-to-face; group	-	Inhibition	COR > NSL

Flynn & Richert, 2018	147	9.1 (1.5)	Non-playing control (C) vs. aerobic PA with low CE (AER) vs. sedentary video game (VID) vs. exergame with high CE (ExH)	C: 49.9 (40.6); AER: 140.7 (53.3); VID: 49.5 (53.0); ExH: 116.3 (72.9)	20	n.a.; virtual; individual	-	Inhibition, flexibility	Inhibition, shifting: ExH & VID > AER & C
Jäger et al., 2014	104	7.9 (0.4)	Sedentary control (C) vs. Physical games with high CE (PG)	C: 89.7 (9.3); PG: 156.8 (14.1)	20	PE during school; face-to-face; team games	Covariates	Inhibition, flexibility, working memory	Inhibition: PG > C. Updating, shifting: no differences.
Schmidt et al., 2016	92	11.8 (0.4)	Sedentary control (C) vs. aerobic PA with low CE (AER) vs. sedentary with high CE (COG) vs. aerobic PA with high CE (COMB)	C: 87.9 (9.8); AER: 144.6 (35.4); COG: 102.9 (21.1); COMB: 154.1(25.7)	10	Own classroom during school; face-to-face; group	Mediating variables	Inhibition	COMB & COG > AER & C
Bedard et al., 2021	48	7.0 (1.4)	Sedentary control (C) vs. aerobic PA with low CE (AER) vs. aerobic PA with high CE (COMB)	C: 88.4 (9.8); AER: 164.7 (22.1); COMB: 159.9(11.0)	20	Unused classroom after school; face-to-face; pairs	Covariates	Inhibition, flexibility	COMBO = AER = C
Best, 2012	33	8.1 (1.3)	Sedentary video watching (C) vs. sedentary video game (VID) vs. exergame with low CE (ExL) vs. exergame with high CE (ExH)	C: 93.1 (2.5); VID: 94.2 (2.2); ExL: 154.8 (3.8); ExH: 157.9 (2.9)	20	Unused classroom after school; virtual; individual	Covariates	Inhibition	ExH = ExL; ExH & ExL > VID & C
Bulten et al., 2022	38	11.9 (0.5)	Sedentary control (C) vs. aerobic PA with low CE (AER) vs. aerobic PA with high CE (COMB)	C: 94.0 (8.0); AER: 150.0 (5.0); COMB: 147.0 (6.0)	20	Unused classroom after school; face-to-face; pairs	Mediating variables	Inhibition, flexibility, working memory	COMBO = AER = C

Jäger et al., 2015	219	11.4 (0.5)	Control (C) vs. cognitive games (COG) vs. aerobic PA (AER) vs. physical games with high CE (PG)	C: 81.9 (10.1); COG: 94.5 (8.7); AER: 150.8 (15.1); PG: 147.8 (17.6)	20	PE during school; face-to-face; team games	Covariates	Inhibition, flexibility, working memory	PG = AER = COG = C
Van den Berg et al., 2016	194	11.8 (0.7)	Aerobic PA (AER) vs. strength PA (STR) vs. coordinative PA (COR)	AER: 127.0 (12.6); STR: 119.7 (9.9); COR: 114.1 (10.6)	12	Own classroom during school; face-to-face; group	Covariates	Inhibition	COR = STR = AER
Wen et al., 2021	145	10.9 (0.3)	Sedentary control (C) vs. soccer (SOC) vs. strength PA (STR) vs. coordinative PA (COR)	C: 89.5 (10.3); SOC: 139.3 (12.1); STR: 135.2 (11.7); COR: 132.6 (12.3)	40	PE during school; face-to-face; team games	-	Inhibition, working memory	COR = STR = SOC; COR & STR & SOC > C.
Egger et al., 2018	216	8.0 (0.4)	Sedentary control (C) vs. aerobic PA with low CE (AER) vs. sedentary with high CE (COG) vs. aerobic PA with high CE (COMB)	C: 94.5 (14.6); AER: 143.3 (18.4); COG: 103.2 (8.3); COMB: 139.1 (15.5)	20	Unused classroom during school; face-to-face; group	-	Inhibition, flexibility, working memory	Shifting: COMB & COG < AER & C. Inhibition, updating: no differences.
Gallotta et al., 2012	138	n.a. [8-11]	Aerobic PA with low CE (AER) vs. sedentary with high CE (COG) vs. aerobic PA with high CE (COMB)	COG: n.a. AER: 146.6 (14.1); COMB: 147.2 (15.5)	50	Own classroom & PE during school; face-to-face; group	-	Inhibition	COMB < COG < AER
Gallotta et al., 2015	116	n.a. [8-11]	Aerobic PA with low CE (AER) vs. sedentary with high CE (COG) vs. aerobic PA with high CE (COMB)	COG: n.a. AER: 146.6 (14.1); COMB: 147.2 (15.5)	50	Own classroom & PE during school; face-to-face; group	-	Inhibition	COMB < COG < AER

Note. CE: Cognitive engagement; PE: Physical education. Green color: Studies that revealed positive effects in favor of cognitively more challenging PA conditions. Yellow color: Studies that found no differences among PA conditions with different cognitive challenge levels. Red color: Studies that found detrimental effects or lower improvement after cognitively more challenging PA conditions.

A univocal synthesis is further limited by differences in employed bout durations. In the duration range most frequently used (10-20 min), acute cognitively challenging bouts at moderate to vigorous intensity resulted in facilitation (Benzing et al., 2016; Budde et al., 2008; Flynn & Richert, 2018; Jäger et al., 2014; Schmidt et al., 2016), no effects (Bedard et al., 2021; Bulten et al., 2022; Best, 2012; Jäger et al., 2015; van den Berg et al., 2016) or even detrimental effects on EFs (Egger et al., 2018). Conversely, longer PA durations (40 and 50 min) elicited both in children and adolescents either no effects (Wen et al., 2021) or lower improvements after cognitively more challenging PA conditions (Gallotta et al., 2012; 2015).

Inconsistences also arise when examining acute cognitively challenging PA studies with similar PA modalities (exergames) and durations (15-20 min; Benzing et al., 2016; Best, 2012; Flynn & Richert, 2018). These inconsistencies could be attributed to differences in the selected sample and the content of control conditions used to manipulate the cognitive challenge level. While Best (2012) and Flynn & Richert (2018) considered younger samples and compared exergaming conditions to completely different PA modalities, Benzing and colleagues (2016) focused on adolescent males and compared various exergames with differing cognitive challenge levels. Consequently, it is likely that experimental conditions not only differed in cognitive challenge but also in physical task demands, not allowing to disentangle individual and combined effects of physical and cognitive challenges on EFs. Additionally, the three studies did not adapt the dosage of cognitive challenge to the responsiveness of participants with different individual characteristics.

Analogously to what has been proposed for the individualization of quantitative task characteristics (Herold et al., 2021), it may be crucial to also individualize the cognitive demands of PA to the individual performance that varies as a function of a broad range of individual biological, developmental, physical, and cognitive characteristics (Herold et al., 2021; Ishihara et al., 2021; Lubans et al., 2022; Pesce, 2009). Notably, the potential moderating role of individual characteristics is rarely considered in acute cognitively challenging PA studies (Schmidt et al., 2021) with diverging preliminary evidence (e.g., Hwang et al., 2021; Jäger et al., 2015). It is still debated, for example, if individuals with poorer baseline performance (cognitive, physical) benefit the most due to greater room for improvement (Drollette et al., 2014; Hwang et al., 2021; Ishihara et al., 2021) or if cognitively challenging bouts of PA are more beneficial for those who are cognitively and physically better equipped to capitalize on it (Herold et al., 2021; Jäger et al., 2015).

Lastly, the inconsistent pattern of results of acute cognitively challenging PA studies might be further explained by differences in contextual factors (see Table 1). These factors refer to PA external and situational conditions, including the delivery style (i.e., the instructional style), the delivery mode (i.e., the way it is delivered, such as face-to-face or virtual reality), and the social and physical environment (i.e., where and with whom the exercise is performed; Pesce et al., 2021, Vella et al., 2023). As suggested for chronic PA effects, more consistent and stronger positive evidence for cognitive improvements emerges for delivery styles in which educators generate engagement and positive affective states (Diamond & Ling, 2016; Pesce et al., 2021). To effectively enhance positive affective states, various delivery styles have been proposed, ranging from evidence-based styles such as music (Terry et al., 2020) to theory-driven styles such as positive feedback that fulfills basic psychological needs (Fransen et al., 2018). In particular, the *macro theory of positive functioning*, which combines elements of *self-determination* (Ryan & Deci, 2000) and *broaden and build theories* (Fredrickson, 2004), suggests that higher levels of basic need satisfaction lead to increased positive affect. This, in turn, promotes cognitive functions by broadening perspectives and fostering engagement (Stanley & Schutte, 2023). In acute PA-cognition research, specifically, it has been hypothesized that the increase in affective states during PA may transiently benefit subsequent cognitive performance by compensating the depletion of limited self-regulation resources consumed by the PA task itself (i.e., *overcompensation hypothesis of the self-control model*; Audiffren & André, 2015; Baumeister et al., 2007; Tice et al., 2007). However, this issue is still debated (e.g., Carter & McCullough, 2014).

To date, the influence of the affect-eliciting properties of different delivery styles in the relationship between acute cognitively challenging bouts of PA and children's EFs remains largely unexplored. No studies manipulated this contextual factor, and only two studies considered the mediational role of affective states, yielding inconsistent results (Bulten et al., 2022; Schmidt et al., 2016). Most studies either did not measure affective states at all or merely controlled for them as potential covariates (see Table 1). Inconsistent evidence might also be explained by differences in employed environments ranging from individual to group or team, and delivery modes spanning from face-to-face to virtual reality (see Table 1). This assumption is based on evidence suggesting that environmental settings and delivery modes might act as facilitators or constraints of PA effects (Pesce et al., 2021) and trigger differential underlying mechanisms such as for example immersion and presence for virtual reality contexts of PA (Sweetser & Wyeth, 2005).

Taken together, transient EFs benefits are largely influenced by the interaction of different qualitative and quantitative PA task characteristics, contextual factors, and individual characteristics (see Figure 1). Task characteristics may be qualitative as cognitive complexity (or challenge) and quantitative as duration (Lubans et al., 2022; Pesce, 2012). Contextual factors range from the delivery style to the delivery mode and features of the environment in which the PA takes place (Pesce et al., 2021; Vella et al., 2023). Individual characteristics that influence children's responsiveness to PA encompass a broad range of biological, developmental, physical, and cognitive factors (Herold et al., 2021; Ishihara et al., 2021; Lubans et al., 2022; Pesce, 2009).

To address this research gap, it is crucial to systematically investigate dose-response relationships within the frame of qualitative and quantitative PA characteristics, while also considering contextual factors and related affective states, and finely tuning task demands to the individual performance. From an education perspective, these insights have the potential to inform the design of active breaks beneficial for children's cognitive functions.

The research project

The studies included in this dissertation are part of the research project "School-based physical activity and children's cognitive functioning: The quest for theory-driven interventions", founded by the Swiss National Science Foundation (Eccellenza Grant: 181074). The overarching aim of the project was to (a) investigate the effects of designed bouts of PA on children's cognition, and (b) transfer the insights into chronic PA interventions for the school setting. Within the overall aim (a), the included within-subject crossover studies with post-test comparisons focused on different PA characteristics: Cognitive challenge level (*study I*), bout duration (*study II*), and feedback form (*study III*).

In all studies, we used a specifically developed exergame (Martin-Niedecken et al., 2020) as an intervention in the school setting. Exergaming, also known as active video gaming, is an enjoyable form of PA that combines physical and cognitive challenges and integrates visual and auditory immediate feedback systems in a virtual reality scenario (Benzing & Schmidt, 2018; Davis et al., 2022). It seems a promising tool to effectively manipulate and individualize both physical and cognitive challenges of the bout and induce affective states in a highly controlled and yet ecologically valid fashion (Benzing & Schmidt, 2018).

Exergame sessions were performed individually. Children completed different movements while being immersed in an underwater race-game scenario with different colored gates. Each gate provided information regarding specific movements and cognitive tasks. Jumps, squats, skipping, and deep lunges (50% of total movements) were used to maintain HR constant at approximately 65% HR_{max}, monitored through HR sensors. To manipulate the cognitive challenge, punches and catching sideway points (50% of total movements) were designed to mirror attentional allocation processes involved in the attention network paradigm (Fan et al., 2009), including anticipatory cues that alerted and oriented attention and targets that required interference control. The level of cognitive challenge was manipulated through an ascending number of distracting stimuli and misleading cues. Exergaming task examples can be found here: https://vimeo.com/759054046.

Study I – Cognitive challenge level

Study I, "Acute exercise and children's cognitive functioning: What is the optimal dose of cognitive challenge?" (Anzeneder et al., 2023a), aimed to: (1) Shed light on which cognitive challenge level in acute exergame-based PA benefits children's executive control the most; (2) extend the focus beyond the most studied executive control to include alerting and orienting network performances and interactions; and (3) explore whether individual characteristics moderate cognitive challenge effects.

The rationale for this study was twofold. First, previous acute cognitively challenging PA studies with children and adolescents investigated cognitive challenge effects but quantitative PA characteristics covaried with experimental conditions (Benzing et al., 2016; Best, 2012; Flynn & Richert, 2018). Second, none of these studies individualized the cognitive demands through adaptation to the ongoing individual performance. According to the *cognitive stimulation hypothesis* (Best, 2010; Pesce, 2012; Tomporowski et al., 2015), we hypothesized that a higher cognitive challenge level would elicit larger executive control gains. Concerning the second and third aim, no a-priori hypothesis was formulated due to limited evidence base.

A total of 103 children (M_{age} = 11.1, *SD* = 0.9, 48% female) participated weekly in one of three 15-min exergame conditions, followed by an Attention Network test (Fan et al., 2009). Exergame sessions were designed to have different cognitive challenge levels (low, mid, high in a counterbalanced order), continuously adapted to the ongoing individual performance. During exergame sessions, perceived cognitive engagement and physical exertion, objective HR, valence, arousal, and stress were assessed.

Results showed that the high-challenging condition was perceived as more cognitively and physically demanding, less pleasant and arousing, and more stressful compared to the other two conditions that, in turn, did not differ from each other. Objective HR confirmed the intended similarity of physical demands among conditions. As concerns cognitive outcomes, the cognitively high-challenging bout benefitted children's executive control the most with faster RTs and no speed-accuracy trade-off. The efficiency of alerting and orienting networks was unaffected by the cognitive challenge level. Among individual characteristics, biological sex moderated cognitive challenge effects. In males only, the benefit of executive control seemed to be due to an interaction of executive control and orienting. Specifically, males exhibited an increased ability to maintain executive control efficiency also when spatial attentional resources could not be allocated in advance to support conflict resolution.

Consistent with our hypothesis, the beneficial effects of a high cognitive challenge level on executive control support the assumptions of the *cognitive stimulation hypothesis* (Best, 2010; Pesce, 2012; Tomporowski et al., 2015). Results align with those of previous acute cognitively challenging PA studies (Benzing et al., 2016; Budde et al., 2008; Flynn & Richert, 2018; Jäger et al., 2014; Schmidt et al., 2016) and neuroimaging studies suggesting larger cognitive-challenge dependent changes in cortical activity (Becker et al., 2023). The main effect on executive control and the moderating role of individual characteristics, along with the absence of effects for alerting and orienting, as well as the results of manipulation checks are addressed in the general discussion with a comparative lens across the three studies.

Study I has extended existing evidence by manipulating the cognitive challenge level in acute bouts of PA in an individualized manner. Results underline the relevance of the cognitive challenge "dose" in acute PA to increase children's EFs and inform the choice of the optimal cognitive challenge level for *study II*.

Study II – Bout duration

Study II, "Dose-response relation between the duration of a cognitively challenging bout of physical exercise and children's cognition" (Anzeneder et al., 2023b), aimed to: (1) Investigate which bout duration of the identified optimal cognitive challenge level benefits children's executive control most; (2) extend the focus to alerting and orienting network performances and interactions; and (3) explore whether individual characteristics moderate duration effects.

The rationale for this study was threefold. First, although a curvilinear relationship between duration and children's EFs has been hypothesized (Schmidt et al., 2021), none of the previous acute cognitively challenging PA studies with children manipulated bout duration. Second, in previous PA studies without cognitive challenge, dose-response relationships have been mostly investigated by manipulating PA intensity and less frequently duration (Lubans et al., 2022). Third, the few studies with children that have manipulated the duration of an acute bout are hardly comparable due to differences in PA intensity and modality (Graham et al., 2021; Hatch et al., 2021; Howie et al., 2015; van den Berg et al., 2018). According to the *arousal theory* (Audiffren et al., 2009; Lambourne & Tomporowski, 2010), we hypothesized an inverted U-shaped function between bout duration and children's executive control, with intermediate durations eliciting larger gains compared to shorter and longer durations. Concerning the second and third aim, no a-priori hypothesis was formulated due to limited evidence base.

A total of 104 children (M_{age} = 11.5, *SD* = 0.8, 51% female) participated weekly in one of four exergame conditions, followed by an Attention Network test (Fan et al., 2009). Exergame sessions were designed to have a high cognitive challenge level (individually adapted within a fixed range) but differing bout durations (5 [C5], 10 [C10], 15 [C15], 20 min [C20] in a counterbalanced order). During exergame sessions, perceived cognitive engagement and physical exertion, objective HR, valence, arousal, and stress were assessed.

Results showed that C5 was perceived as less cognitively and physically demanding than C15 and C20, whereas the shortest (C5 vs. C10) and longest conditions (C15 vs. C20) were perceived as equally demanding. Objective HR confirmed the intended similarity of physical demands among conditions. No differences among conditions emerged for valence and arousal. Only C20 was perceived as more stressful than C5. As concerns cognitive outcomes, C15 benefitted children's overall information processing speed the most with faster overall RTs and no speed-accuracy trade-off. The efficiency of executive control, alerting, and orienting was unaffected by bout duration. Among individual characteristics, habitual PA level moderated the duration effect on the interactive functioning of executive control and orienting. Specifically, more active children seemed better able to capitalize on an optimal (15 min) acute PA duration for maintaining executive control efficiency also under disadvantageous spatial attention conditions.

An intermediate duration (15 min) benefitted children's information processing speed the most, in line with assumptions of *cognitive-energetic theories* (Audiffren & André, 2015; Baumeister et al., 2007; Sanders, 1983), but did not affect executive control as hypothesized. Selective duration effects on lower-order processes are consistent with evidence of aerobic PA studies with adolescents (Hatch et al., 2021) and adults (Chang, Chu, et al., 2015). However, a thorough comparison is hindered by differences in task characteristics, contextual factors, and individual characteristics. The main effect found on information processing speed but not on any attention network, the moderating role of individual characteristics, as well as the results of manipulation checks are addressed in the general discussion with a comparative lens across the three studies.

Study II has extended existing evidence by manipulating the duration of acute cognitively challenging bouts of PA. Results support a dose-response relationship between PA duration and children's information processing speed and inform the choice of the optimal duration for *study III*.

Study III – Feedback form

Study III, "Acute cognitively challenging exercise as "cognitive booster" for children: Positive feedback matters!" (Anzeneder et al., 2024), aimed to: (1) Investigate the effect of different feedback forms (no feedback [NO-FB], standard acoustic environment [ST-FB], standard acoustic environment combined with positive feedback [PO-FB]) during an acute, 15 min, cognitively high-challenging exergaming bout on children's executive control, as well as alerting and orienting performances and interactions; (2) test whether affective states (valence and arousal) also differ between feedback forms; and (3) examine whether affective valence and arousal mediate the effect of feedback on cognitive performance. The rationale for this study was twofold. First, although the relevance of the delivery style has been confirmed in chronic PA studies (Diamond & Ling, 2016; Pesce et al., 2021), this issue remains largely unexplored in acute cognitively challenging PA studies. Second, only two acute studies considered the mediational role of affective states, yielding inconsistent results (Bulten et al., 2022; Schmidt et al., 2016). Based on piecemeal evidence of enhanced positive affective states after positive feedback (Fransen et al., 2018) and exposure to music (Terry et al., 2020), we hypothesized that feedback conditions would differentially impact affective states (PO-FB > ST-FB > NO-FB). Based on the *overcompensation hypothesis of the self–control model* (Audiffren & André, 2015), according to which cognitive resources are less depleted in presence of positive affective states, we hypothesized that feedback forms would differentially impact cognitive performance, mediated by affective states (PO-FB > ST-FB > NO-FB).

A total of 100 children (M_{age} = 11.0, *SD* = 0.8, 49% female) participated weekly in one of three exergame conditions lasting 15 min, followed by an Attention Network test (Fan et al., 2009). Exergame sessions were designed to have a high cognitive challenge level (individually adapted within a fixed range) but differing feedback forms (NO-FB, ST-FB, PO-FB in a counterbalanced order). During NO-FB, children played the exergame without any auditory signal and received visual feedback within the exergame regarding the correctness and accuracy of their movements and the progression of the difficulty levels. During ST-FB, visual feedback was accompanied by motivating music that increased in tempo with the difficulty level, along with sound effects integrated into the standard version of the exergame. During PO-FB, children played the exergame in the standard acoustic environment, and researchers provided positive standardized verbal feedback (15 feedback every 5 min). During exergame sessions, valence, arousal, objective HR, perceived cognitive engagement and physical exertion, and flow were assessed.

Results showed that PO-FB was perceived as more pleasant compared to the other two conditions, while ST-FB and NO-FB did not differ from each other. In PO-FB, flow experience was also significantly higher compared to the other two conditions. All conditions were perceived as equally cognitively and physically demanding. Objective HR confirmed the intended similarity of physical demands among conditions. As concerns cognitive outcomes, PO-FB benefitted children's executive control most, with faster RTs and no speed-accuracy trade-off. The efficiency of alerting and orienting networks was unaffected by feedback form. Individual characteristics did not moderate feedback effects. The increment in affective valence elicited by PO-FB was associated with subsequent executive control performance; however, affective states did not mediate feedback effects on executive control.

Consistent with our hypothesis, positive feedback enhanced children's affective states the most and benefitted executive control more than other feedback forms. Results are in line with "capacity boosting" emotional-energetic mechanisms proposed for chronic PA effects (Pesce et al., 2021) and support the assumptions of the *overcompensation hypothesis of the self-control model* (Audiffren & André, 2015). The absence of mediational effects is in contrast with previous studies (Schmidt et al., 2016) and suggests the presence of further possible underlying mechanisms such as feedback-elicited increments in perceived competence (Fransen et al., 2018). The main effect found on executive control but not on any attention network, the absence of moderating effects of individual characteristics, the role of positive affective states, as well as the results of manipulation checks are addressed in the general discussion with a comparative lens across the three studies.

Study III has shown that positive feedback during an acute cognitively challenging PA creates favorable conditions for the promotion of children's affective states and executive control performance. Results highlight the importance of considering the interplay of task characteristics and contextual factors.

Discussion

The overarching aim of the research project was to identify task characteristics and contextual factors of acute bouts of PA for informing the design of school-based PA breaks beneficial for children's cognition. Given the inconclusive pattern of results of acute cognitively challenging PA studies with children, an integrative framework that encompasses complementary effects of task characteristics, contextual factors, and individual characteristics was adopted (Figure 1). Task characteristics and contextual factors were manipulated systematically, while also controlling for individual differences in responsiveness to the bout of PA. Results provided evidence of dose-response relationships of both qualitative and quantitative PA task characteristics with cognitive outcomes, further modulated by contextual factors and individual differences, suggesting a nuanced pattern of moderators that complexify and differentiate the acute PA-cognition relationship.

Physical activity task: Qualitative and quantitative characteristics

As concerns qualitative characteristics, s*tudy I* showed that the cognitive challenge level matters. Children exhibited largest benefits in executive control after playing the exergame with the highest cognitive challenge level. This result supports the *cognitive stimulation hypothesis*, assuming that cognitive demands inherent in movement actions that are novel and performed under variable situational conditions, rather than being fully automatized and repetitively performed in a constant environment, may foster EFs both transiently and in the long-term (Best, 2010; Pesce, 2012; Tomporowski et al., 2015). Interestingly, recent neuroimaging evidence suggested that beneficial effects on EFs of complex motor tasks with high cognitive demands are paralleled by more efficient cortical processes, as reflected, for example, in enhanced power of theta frequency in the prefrontal cluster (Becker et al., 2023). Our study represents a step forward compared to the only study that manipulated the cognitive demands within the same (exergaming) modality (Benzing et al., 2016). While extending to children Benzing and colleagues' (2016) findings that a cognitively high-challenging condition benefitted adolescents' EFs most, our study allowed overcoming the limitation of a fixed external load by adjusting the cognitive demands individually to ensure a more homogeneous level of internal load.

As regards quantitative characteristics, *study II* did not support the hypothesis of differential effects of bout duration on executive control. Instead, it showed that the duration of a cognitively high-challenging bout benefitted only lower-order cognitive processes, with faster information processing speed after a 15 min bout. Results likely reflect altered psychological states, such as increased arousal and activation, which facilitate performance in subsequent cognitive tasks (i.e., *arousal theory*; Audiffren et al., 2009). Concerning intensity, in all studies the exergame was performed at approximately 65% HR_{max}. The intensity was chosen according to meta-analytic evidence showing more consistent beneficial effects of moderate to vigorous intensities (Chang et al., 2012; Ludyga et al., 2016; McMorris & Hale, 2012; Moreau & Chou, 2019; Pontifex et al., 2019). Within this range, a moderate intensity was used to prevent overload due to possible additive effects of physical exertion and cognitive engagement. Indeed, *cognitive-energetic models* (Baumeister et al., 2007; Sanders, 1983), applied to the relationship between acute PA and following cognitive performance (Audiffren & André, 2015), predict negative effects when a too intense or too long PA induces a sub-optimal state that depletes effort. Moreover, it has been argued that in dual-task paradigms, moderate intensities combined with cognitive load effectively increase prefrontal cortex activity that, in turn, is related to EF performance (Kimura et al., 2022).

Physical activity context: Delivery style and environmental features

Extending the focus to contextual factors, *study III* showed that a delivery style combining music with positive feedback during a 15 min, cognitively high-challenging acute bout created favorable conditions for the joint promotion of children's executive control performance and affective states. Moreover, the extent to which positive feedback increased affective valence was associated with executive control performance. These findings support the assumptions of the *overcompensation hypothesis of the self-control model* (Audiffren & André, 2015). As hypothesized, the combination of motivating music and positive feedback may have generated optimal affective states, which overcompensated the depletion of self-control strength due to physical effort. Indeed, the *strength model of self-control* (Baumeister et al., 2007; Tice et al., 2007) considers positive affective states as crucial to enhance self-control and effort that in turn improve EFs (Audiffren & André, 2015). However, even if associated with executive control, affective states did not mediate feedback effects. The absence of a mediation of valence and arousal adds evidence to previous acute cognitively challenging PA studies testing a potential mediation of affective states, but leading to inconsistent conclusions (Bulten et al., 2022; Schmidt et al., 2016). Schmidt et al. (2016) found evidence for mediation, whereas Bulten et al. (2022) did not, suggesting that the absence of mediation might be due to a ceiling effect in affective responses to the experimental manipulation. Our study, instead, did not exhibit this limitation, since manipulation check variables, along with affective states and the executive control performance of interest, seemed to be differentially sensitive to the positive feedback condition compared to the other feedback forms. Nevertheless, our results cannot support the notion that affective states are psychological mechanisms underlying the transient effect of a cognitively challenging bout of exercise on children's executive control. Speculatively, the provision of positive feedback, encouragement, and optimal challenges combined with the creation of a structured environment might not only have elicited positive affective states but also enhanced perceived competence that, in turn, might have mediated feedback effects on executive control (Fransen et al., 2018; Hohnemann et al., 2022; Peifer et al., 2020).

As concerns the delivery mode of exergaming, in all three studies children perceived all experimental conditions as highly enjoyable and arousing. This confirms that exergame-based interventions offer engaging and pleasant forms of PA (Lee et al., 2017). Indeed, it has been suggested that enjoyment is directly linked to the extent to which exergames integrate multimodal feedback, physical and cognitive challenges, and rewards (Lyons, 2015) and, thus, elicit an optimal flow experience (i.e., a positive experience of being fully absorbed in an optimally challenging task; Csikszentmihalyi, 1990). In *study III*, affective measures were complemented by the assessment of flow. As expected, children reached the highest flow state in the feedback form combining music with positive feedback. Indeed, it seems that positive feedback enhances the likelihood of flow because it reinforces individuals' feeling of confidence in task completion (Peifer et al., 2020). Instead, the standard acoustic environment was perceived as equally flow–eliciting as the no feedback condition. These effects may be attributed to the unique exergaming environment, rich in visual animation and immersive elements (Martin–Niedecken et al., 2020). This environment has been shown to induce positive affective responses by shifting attention from interoceptive to visual–acoustic exteroceptive stimuli (Jones & Ekkekakis, 2019). The immersion may have captured children's attention to a point that adding music and sound effects as in the standard acoustic environment condition was not effective in further enhancing the experience of flow (Cummings & Bailenson, 2016).

Individual characteristics: Biological sex and habitual physical activity

As concerns individual characteristics that might moderate PA effects (Herold et al., 2021; Pesce, 2009), among biological, developmental, physical, and cognitive factors tested, only biological sex and habitual PA moderated cognitive challenge and duration effects on the interactive functioning of executive control and orienting (*study I* & *II,* respectively). Instead, feedback effects were generalizable with respect to the considered individual characteristics (*study III*). Sex differences moderated the effect of cognitive challenge on the interactive functioning of executive control and orienting networks (*study I*). Intriguingly, when engaging in exergaming with the highest cognitive challenge, males were not only most efficient in executive control but maintained this efficiency also when spatial attention could not be allocated in advance. In other words, they were able to buffer the negative effects of lacking spatial valid information. Results are consistent with an adult study without PA (Li et al., 2021) showing different hemispheric lateralization of attentional networks, with males being less influenced by cue validity.

Beyond biological interindividual differences as sex, the only further individual characteristic that influenced the acute PA-cognition relationship was behavioral and physical in nature. In *study II*, habitual PA level moderated the effect of bout duration on the interactive functioning of executive control with spatial disengaging. Interestingly, children with higher habitual PA levels were seemingly better able to exploit the optimally arousing effect of a 15 min bout for maintaining executive control efficiency, also under disadvantageous spatial attention conditions. In other words, they were able to buffer the negative effects of misleading spatial information that did not affect their executive control efficiency. Results are in line with previous acute cognitively challenging PA studies showing beneficial effects on EFs only in children who are physically better equipped to capitalize on it (Jäger et al., 2015).

Task individualization and effectiveness of experimental manipulation

In all studies, physical and cognitive task demands were continuously adapted to children's ongoing individual performance, ensuring that the task was not under- or overloading (*optimal challenge point paradigm*; Guadagnoli & Lee, 2004). Indeed, considering that overall stimulation is determined by the interaction of physical and cognitive task demands, contextual factors, and individual resources and abilities (DiDomenico & Nussbaum, 2008), it is crucial to finely tune the overall stimulation of the bout by tailoring and individualizing both quantitative and qualitative PA task demands to match with individual abilities and skills. From a cognitive perspective, this ensures that the mental load matches individual available resources allocated to perform the task (Paas et al., 2003), resulting in greater enjoyment (Abuhamdeh & Csikszentmihalyi, 2012). Several manipulation check variables were collected. Interestingly, in all studies, children did not discriminate cognitive engagement from physical exertion. Developmental studies have shown that children as young as 8 years can successfully complete tasks that involve introspection (Roebers et al., 2009). Nevertheless, the current findings rather align with evidence syntheses of neurophysiological studies, which suggest that multimodal loads might converge into a more undifferentiated perception of overall load (e.g., Charles & Nixon, 2019). One possible explanation for the limited differentiation in load perception between cognitive and physical domains is that cognitive engagement and physical exertion rely on similar cortical brain areas (Lopez-Gamundi et al., 2021; Westbrook et al., 2019).

Cognitive outcomes not impacted by experimental manipulation

In all studies, alerting and orienting performances were not differentially affected by any experimental condition. The manipulation of PA duration seems not to influence any attention network, while the manipulation of cognitive challenge and feedback influenced only executive control. Speculatively, the fact that only executive control but no other attention networks were sensible to cognitive challenge and feedback might be interpreted according to evidence suggesting selectively larger effects in performance for tasks requiring greater executive control (Lubans et al., 2022). The absence of effects on alerting and orienting performances is in line with available evidence that neither an acute demanding and varied spinning task (Chang, Pesce, et al., 2015) nor routine aerobic PA (van den Berg et al., 2018) seems to influence these networks and might depend on ANT–R indices reliability: The higher within–subject variance found for alerting and orienting compared to executive control indices suggests that in the context of within–subjects designs, the first probably have lower statistical power than the latter (MacLeod et al., 2010).

Lastly, effects on executive control (*study I* & *III*) and information processing (*study II*) were limited to RTs, while accuracy of performance indices was unaffected by experimental manipulation. The fact that accuracy was not sensitive to PA task- and context-related factors also emerges from evidence syntheses (e.g., Paschen et al., 2019) and previous acute cognitively challenging PA studies with children that showed intervention effects on RTs only (Best, 2012; Flynn & Richert, 2018; Gallotta et al., 2012; Jäger et al., 2014; Schmidt et al., 2016). It has been claimed that selective effects might be due to different task parameters, such as long stimulus duration and inter-stimulus intervals, which may bias results in favor of RTs (Pontifex et al., 2019). Furthermore, instructions with reaction speed prioritization may lead participants to trade accuracy for speed (Themanson et al., 2008). However, both interpretations are less likely to apply to our studies in which inter-stimulus intervals validated for children were used and standardized test instructions were closely followed.

Limitations

The research project has limitations that should be noted. Considering the overall aim to identify optimal PA task characteristics (*study I & II*) or contextual factors (*study III*), we did not include a sedentary control group. This hindered disentangling physical exertion, and PA task- and context-related effects. Moreover, due to time constraints imposed by schools, we did not include a pre-test assessment for cognitive functions. Future studies should include a sedentary control group and utilize a within-subject crossover pre- and post-test design. In this design, all participants engage in PA and sedentary control conditions in a counterbalanced order and individual differences and learning effects can be controlled (Pontifex et al., 2019).

Second, according to the *cognitive stimulation hypothesis*, PA demands were specifically designed to mirror the ANT paradigm and, thus, might have primed attention effects (Moriarty et al., 2019). Previous evidence suggests that several distinct neural mechanisms are involved in attention priming and that priming occurs at multiple stages of perceptual processing (Kristjánsson & Ásgeirsson, 2019). These underlying mechanisms resemble those of the c*ognitive stimulation hypothesis* (Best, 2010; Pesce, 2012; Tomporowski et al., 2015). However, there are notable differences between the computerized, seated ANT task and the whole-body engagement in the exergame, which requires gross-motor control (Koziol et al., 2014). Additionally, priming effects are typically of shorter duration (Kruijne & Meeter, 2015), making it less likely to interpret our results solely in terms of overall priming effects. However, it remains unclear if, besides near transfer effects of the motor and cognitive demands of the exergaming on ANT performances, far transfer effects on other EFs can also be elicited (Smid et al., 2020). Future studies should investigate PA effects on a variety of more and less distant cognitive measures and complement these by multiple levels of analysis, such as neuroimaging, to understand the neurobiological mechanisms that drive the changes in behavioral performance.

Third, we used the Borg rating scale of perceived exertion and its adapted version for cognitive engagement to assess children's perceived load. In *study I*, exergaming demands were manipulated to generate three cognitive challenge levels with comparable physical intensity. However, children perceived the low and mid conditions as equally demanding, and the high challenge condition as more cognitively and physically demanding. Future studies should determine the threshold needed by children to discriminate different challenge levels; validate existing subjective cognitive engagement measures (e.g., NASA Task Load Index); and complement them with objective assessments such as brain activity or HR variability (Brockhoff et al., 2022).

Fourth, in all studies the sample size was powered for the main analyses on the primary outcome (i.e., executive control); the additional exploratory analyses considering background characteristics as covariates may have been underpowered to detect their influence and ensure generalizability to children differing in those characteristics. Future studies should address this issue by selecting an appropriate sample size for these types of analyses.

Fifth, in all studies the exergaming was played individually, thus not allowing to capitalize on the beneficial effects elicited by social interaction (i.e., less psychological stress, higher well-being, enhanced immersion of players; Lee et al., 2017). However, the individual play was chosen for the present project to prioritize the manipulation and ongoing individualization of physical and cognitive challenges. Further studies should explore different social interaction modes (cooperative vs. competitive) in exergaming, also considering individual characteristics such as age, preferences, and motivation (Pesce et al., 2021).

Conclusion, prospects, and recommendations

The integrated framework (Figure 1) and systematic investigation adopted in the current research project provide useful information on what works (i.e., qualitative PA modality and quantitative dose), for whom (i.e., individual differences), under which circumstances (i.e., contextual factors) and why (i.e., underlying mechanisms). A single cognitively high-challenging bout of PA, with challenges adapted to the ongoing individual performance, lasting 15 min, and combining music with positive feedback seems to optimally foster children's cognitive functions. These features that have collectively emerged from the present research project as optimal to reap largest effects from a single bout of PA largely overlap, in general terms, with the recommendations provided regarding chronic PA. Indeed, Diamond and Ling (2020, p. 501) highlighted the following key characteristics to design interventions that favorably impact EFs in the long-term: "practice conditions that continuously challenge EF processes; learning tasks that elicit commitment and emotional investment; delivery styles that include supportive instructors; and performance that leads to feelings of competence and self-confidence". In sum, the findings of this research project extend evidence on the complementary role of task, contextual and individual characteristics in explaining the effectiveness of acute PA in transiently enhancing children's cognitive functions relevant to learning and academic achievement.

Prospect for future research

Prospects for further research to bring this line of research closer to the school context are at least twofold. First, future studies should complement the search for a cognitively optimal challenge point with the investigation of additive or interactive effects of social interaction (Best, 2012) that is a key feature of school learning (de Felice et al., 2023). The role of social interaction in enhancing cognitive functioning relies on theories that link it to the development and maintenance of EFs (Perry et al., 2019). To capitalize on social interaction, future exergame-based interventions should be designed trading technology and related ongoing individualization of cognitive demands for group-delivery. In a 3 x 2 design, the effects on EFs could be tested contrasting acute bouts of PA with similar dose (15 min, moderate intensity) delivered individually or in a group to a sedentary control group, with all three groups targeted to have different levels of cognitive demands (low vs. high). This would allow a theory-based, individual and combined investigation of physical exertion, cognitive challenge, and social interaction effects. In a second step, a similar study design (individual PA vs. group PA vs. sedentary control, all with low vs. high cognitive demands) should be investigated with a chronic intervention design. It has been hypothesized that self-control capacity that transiently decreases after a single bout of PA should increase in the long-term after repeated bouts of PA (i.e., chronic PA; Audiffren & André, 2015). Replicating the 3 x 2 design in a chronic study design would allow to bridge the gap between acute and chronic research and investigate their differential effects on cognitive performance.

Second, considering the time constraints faced by teachers because of physically non-active educational priorities (e.g., STEM goals), one viable solution to also prioritize PA might be to integrate physically active learning of main school subjects into exergaming to test long-term effects on EFs and academic achievement. Future studies might capitalize on the highly individualizable and scalable features of learning tasks offered by closed-loop processes of virtual reality technology. Relying on the theoretical framework of *embodied cognition* (Barsalou, 2008; Wilson, 2002), a virtual reality environment might be a motivating way for children to successfully learn by engaging in physically active learning. Indeed, PA and movement skills may be "carriers" of subject matters, acting with lower load on working memory compared to abstract learning without movement (*evolutionary upgrade of cognitive load theory*; Paas & Sweller, 2012). It has been suggested that the relevance of physical movements for learning tasks (i.e., whether bodily movement is related to subject matters) and the integration of physical movements with learning tasks (i.e., whether bodily movement is connected temporally with subject matters) are critical factors in determining the effectiveness of movement-based learning (Mavilidi et al., 2022). In a 2 x 2 design, the individual and combined effects of physical exertion and relevance-integration dyads on EFs and academic achievement could be tested in a chronic exergame-based intervention contrasting: sedentary control condition unrelated to subject matters performed during recess between academic learning phases vs. active breaks unrelated to subject matters performed during recess between academic learning phases (low relevance, low integration) vs. sedentary control condition learning subject matters during academic learning phases vs. physically active learning of subject matters during academic learning phases (high relevance, high integration).

Recommendations for practice

The current research project has meaningful implications for school practice. Single cognitively challenging bouts of PA can be used in learning contexts to elicit transient cognitive and positive affect enhancements that might help children concentrate optimally and stay on-task in a following academic learning phase. The evidence that emerged from the present research project may be transitioned into practical recommendations to design "cognitively boosting" PA breaks for schools. To this aim, it is essential to consider the following three aspects.

First, the cognitive challenge matters. Beyond exergaming, cognitive challenge can also be effectively incorporated into PA games. Indeed, it has been proposed to apply principles of contextual interference, mental control, and discovery (Tomporowski et al., 2015). Specifically, contextual interference refers to varying PA game conditions that require children to make unpredictable sequences of actions. Mental control refers to the features of stopping games (requiring withholding prepotent responses), updating games (requiring playing with information held in mind), and switching games (requiring changing action rules and stimulus-response associations within the game). Discovery refers to open-ended PA tasks, in which the start and the goal are defined but not the process to pursue the goal (requiring searching for multiple solutions to a motor problem). Furthermore, novelty, diversity, individualization, and effort seem essential ingredients to render active breaks meaningful for cognitive enhancement (Moreau & Conway, 2014; Pesce et al., 2016). Indeed, varying and individualizing the demands of a PA task allows for keeping children on the "learning curve", which is the stage of learning with major cognitive engagement (Tomporowski et al., 2015).

Second, the duration matters. While in the literature short active breaks (< 20 min) with at least moderate intensity are recommended and used (Masini et al., 2022), our research suggests that the duration within this range to elicit cognitive benefits and enhance affective states is 15 min. This duration is relatively long and cannot be interspersed among academic learning phases in a random and unplanned fashion. School principals, made aware of the cognitive benefits of active breaks, should formally plan the systematic inclusion of 15 min active breaks during school time and monitor with teachers their feasibility, implementation, and adaptation to school needs.

Third, the delivery style matters. The delivery style is a relevant feature of the PA context which sets the stage for learning. The present research project has shown that a delivery style characterized by positive feedback coupled with music can amplify the beneficial effects of PA breaks on EFs. Teachers should provide children with enjoyable and playful breaks, combined with supportive and encouraging feedback that can ensure emotional energy necessary to increase intrinsic motivation (Tomporowski et al., 2015) and support basic psychological needs satisfaction (Fransen et al., 2018). Moreover, feedback is relevant not only for its immediate and transient effects on affect and cognitive performance but also for its long-term effects on learning processes. In the long-term, feedback can be used to optimize skill acquisition in motor learning. According to the *OPTMAL theory* (*optimizing performance through intrinsic motivation and attention for learning*) that focuses on the interrelation of cognitive and affective processes (Simpson et al., 2021; Wulf & Lewthwaite, 2016), teachers should provide feedback, particularly on successful trials, to emphasize good performances.

In sum, the effectiveness of active breaks is a matter of good design. Optimal features of active breaks tailor-made to transiently enhance cognitive functions relevant to academic learning should integrate individualized cognitive challenges that are incremental and close to children's upper action capability boundaries, be of sufficient intensity and duration, and – foremost – include positive feedback to elicit positive affective states.

References

Abuhamdeh, S., & Csikszentmihalyi, M. (2012). The importance of challenge for the enjoyment of intrinsically motivated, goal-directed activities. *Personality and Social Psychology Bulletin*, *38*(3), 317–330. doi:10.1177/0146167211427147

Álvarez-Bueno, C., Pesce, C., Cavero-Redondo, I., Sánchez-López, M., Martínez-Hortelano, J.A., & Martínez-Vizcaíno, V. (2017). The effect of physical activity interventions on children's cognition and metacognition: A systematic review and meta-analysis. *Journal of the American Academy of Child and Adolescent Psychiatry, 56*(9), 729–738. doi:10.1016/j.jaac.2017.06.012

Anzeneder, S., Zehnder, C., Martin-Niedecken, A. L., Schmidt, M., & Benzing, V. (2023a). Acute exercise and children's cognitive functioning: What is the optimal dose of cognitive challenge? *Psychology of Sport and Exercise, 66*, 102404. doi:10.1016/j.psychsport.2023.102404

Anzeneder, S., Zehnder, C., Schmid, J., Martin-Niedecken, A. L., Schmidt, M., & Benzing, V. (2023b). Dose-response relation between the duration of a cognitively challenging bout of physical exercise and children's cognition. *Scandinavian Journal of Medicine & Science in Sports*, *33*(8), 1439-51. doi:10.1111/sms.14370

Anzeneder, S., Schmid, J., Zehnder, C., Koch, L., Martin-Niedecken, A. L., Schmidt, M., & Benzing, V. (2024). Acute cognitively challenging exercise as "cognitive booster" for children: Positive feedback matters! *Mental Health and Physical Activity, 27*, 100621. doi: 10.1016/j.mhpa.2024.100621

Audiffren, M., & André, N. (2015). The strength model of self-control revisited: Linking acute and chronic effects of exercise on executive functions. *Journal of Sport and Health Science, 4*(1), 30–46. doi:10.1016/j.jshs.2014.09.002

Audiffren, M., Tomporowski, P.D., & Zagrodnik, J. (2009). Acute aerobic exercise and information processing: Modulation of executive control in a random number generation task. *Acta Psychologica, 132*(1), 85–95. doi:10.1016/j.actpsy.2009.06.008

Barsalou, L.W. (2008). Grounded cognition. *Annual Review of Psychology, 59*, 617–645. doi:10.1146/annurev.psych.59.103006.093639

Baumeister, R.F., Vohs, K.D., & Tice, D.M. (2007). The strength model of self-control. *Current Directions in Psychological Science, 16*(6), 351-255. doi:10.1111/j.1467-8721.2007.00534.x

Becker, L., Büchel, D., Lehmann, T., Kehne, M., & Baumeister, J. (2023). Mobile electroencephalography reveals differences in cortical processing during exercises with lower and higher cognitive demands in preadolescent children. *Pediatric Exercise Science*, 1–11. doi:10.1123/pes.2021-0212

Bedard, C., Bremer, E., Graham, J.D., Chirico, D., & Cairney, J. (2021). Examining the effects of acute cognitively engaging physical activity on cognition in children. *Frontiers in Psychology, 12*, 653133. doi:10.3389/fpsyg.2021.653133

Benzing, V., Heinks, T., Eggenberger, N., & Schmidt, M. (2016). Acute cognitively engaging exergame-based physical activity enhances executive functions in adolescents. *PLoS ONE, 11*(12), e0167501. doi:10.1371/journal.pone.0167501

Benzing, V., & Schmidt, M. (2018). Exergaming for children and adolescents: Strengths, weaknesses, opportunities and threats. *Journal of Clinical Medicine, 7*(11). doi:10.3390/jcm7110422

Best, J.R. (2010). Effects of physical activity on children's executive function: Contributions of experimental research on aerobic exercise. *Developmental Review, 30*(4), 331–351. doi:10.1016/j.dr.2010.08.001

Best, J.R. (2012). Exergaming immediately enhances children's executive function. *Developmental Psychology, 48*(5), 1501–1510. doi:10.1037/a0026648

Biddle, S.J., Ciaccioni, S., Thomas, G., & Vergeer, I. (2019). Physical activity and mental health in children and adolescents: An updated review of reviews and an analysis of causality. *Psychology of Sport and Exercise, 42*, 146–155. doi:10.1016/j.psychsport.2018.08.011

Brockhoff, L., Schindler, S., Bruchmann, M., & Straube, T. (2022). Effects of perceptual and working memory load on brain responses to task-irrelevant stimuli: Review and implications for future research. *Neuroscience and Biobehavioral Reviews, 135*, 104580. doi:10.1016/j.neubiorev.2022.104580

Brydges, C.R., Fox, A.M., Reid, C.L., & Anderson, M. (2014). The differentiation of executive functions in middle and late childhood: A longitudinal latent-variable analysis. *Intelligence, 47*, 34–43. doi: 10.1016/j.intell.2014.08.010

Budde, H., Voelcker-Rehage, C., Pietraßyk-Kendziorra, S., Ribeiro, P., & Tidow, G. (2008). Acute coordinative exercise improves attentional performance in adolescents. *Neuroscience Letters, 441*(2), 219–223. doi:10.1016/j.neulet.2008.06.024

Bulten, R., Bedard, C., Graham, J. D., & Cairney, J. (2022). Effect of cognitively engaging physical activity on executive functions in children. *Frontiers in Psychology, 13*, 841192. doi:10.3389/fpsyg.2022.841192

Campbell, D.J. (1988). Task complexity: A review and analysis. *The Academy of Management Review, 13*(1), 40–52. doi:10.2307/258353

Carter, E.C., & McCullough, M.E. (2014). Publication bias and the limited strength model of self-control: has the evidence for ego depletion been overstimated? *Frontiers in Psychology, 5*, 823. doi: 10.3389/fpsyg.2014.00823

Caspersen, C.J., Powell, K.E., & Christenson, G.M. (1985). Physical activity, exercise, and physical fitness: Definitions and distinctions for health-related research. *Public Health Reports, 100*(2), 126–131.

Chang, Y.K., Chu, C.H., Wang, C.C., Wang, Y.C., Song, T.F., Tsai, C.L., & Etnier, J.L. (2015). Dose-response relation between exercise duration and cognition. *Medicine and Science in Sports and Exercise, 47*(1), 159–165. doi:10.1249/MSS.0000000000000383

Chang, Y.K., Labban, J.D., Gapin, J.I., & Etnier, J.L. (2012). The effects of acute exercise on cognitive performance: A meta-analysis. *Brain research, 1453*, 87–101. doi:10.1016/j.brainres.2012.02.068

Chang, Y.K., Pesce, C., Chiang, Y.T., Kuo, C.Y., & Fong, D.Y. (2015). Antecedent acute cycling exercise affects attention control: An ERP study using attention network test. *Frontiers in Human Neuroscience, 9*, 156. doi:10.3389/fnhum.2015.00156

Charles, R.L., & Nixon, J. (2019). Measuring mental workload using physiological measures: A systematic review. *Applied Ergonomics, 74*, 221–232. doi:10.1016/j.apergo.2018.08.028

Ciria, L.F., Román-Caballero, R., Vadillo, M., Holgado, D., Luque-Casado, A., Perakakis, P., & Sanabria, D. (2023). A call to rethink the cognitive benefits of physical exercise: An umbrella review of randomized controlled trials. *Nature Human Behaviour, 7,* 928-41. doi:10.1038/s41562-023-01554-4

Csikszentmihalyi, M. (1990). *Flow: The psychology of optimal experience*. Harper and Row.

Cummings, J.J., & Bailenson, J.N. (2016). How immersive is enough? A meta-analysis of the effect of immersive technology on user presence. *Media Psychology, 19*(2), 272–309. doi:10.1080/15213269.2015.1015740

Davis, J.C., Killen, L.G., Green, J.M., Waldman, H.S., & Renfroe, L.G. (2022). Exergaming for physical activity: A systematic review. *Journal of American College Health*, 1–9. doi:10.1080/07448481.2022.2103377

Diamond, A. (2000). Close interrelation of motor development and cognitive development and of the cerebellum and prefrontal cortex. *Child Development, 71*(1), 44–56. doi:10.1111/1467-8624.00117

Diamond, A. (2013). Executive functions. *Annual Review of Psychology, 64*, 135–168. doi:10.1146/annurev-psych-113011-143750

Diamond, A. (2020). Executive functions. *Handbook of Clinical Neurology, 173*, 225–240. doi:10.1016/B978-0-444-64150-2.00020-4

Diamond, A., & Ling, D.S. (2016). Conclusions about interventions, programs, and approaches for improving executive functions that appear justified and those that, despite much hype, do not. *Developmental Cognitive Neuroscience, 18*, 34–48. doi:10.1016/j.dcn.2015.11.005

Diamond, A., & Ling, D.S. (2019). Aerobic-exercise and resistance-training interventions have been among the least effective ways to improve executive functions of any method tried thus far. *Developmental Cognitive Neuroscience*, *37*, 100572. doi:10.1016/j.dcn.2018.05.001

DiDomenico, A. & Nussbaum, M.A. (2008). Interactive effects of physical and mental workload on subjective workload assessment. *International Journal of Industrial Ergonomics, 38*(11), 977–983. doi: 10.1016/j.ergon.2008.01.012

Drollette, E.S., Scudder, M.R., Raine, L.B., Moore, R.D., Saliba, B.J., Pontifex, M.B., & Hillman, C.H. (2014). Acute exercise facilitates brain function and cognition in children who need it most: An ERP study of individual differences in inhibitory control capacity. *Developmental Cognitive Neuroscience, 7*, 53–64. doi:10.1016/j.dcn.2013.11.001

Egger, F., Conzelmann, A., & Schmidt, M. (2018). The effect of acute cognitively engaging physical activity breaks on children's executive functions: Too much of a good thing? *Psychology of Sport and Exercise, 36*, 178–186. doi:10.1016/j.psychsport.2018.02.014

Erickson, K.I., Hillman, C., Stillman, C.M., Ballard, R.M., Bloodgood, B., Conroy, D.E., Macko, R., Marquez, D.X., Petruzzello, S.J., & Powell, K.E. (2019). Physical activity, cognition, and brain outcomes: A review of the 2018 physical activity guidelines. *Medicine and Science in Sports and Exercise, 51*(6), 1242–1251. doi:10.1249/MSS.0000000000001936

Eriksen, B.A., & Eriksen, C.W. (1974). Effects of noise letters upon the identification of a target letter in a non-search task. *Perception & Psychophysics, 16*(1), 143–149. doi:10.3758/BF03203267

Etnier, J.L., Nowell, P.M., Landers, D.M., & Sibley, B.A. (2006). A meta-regression to examine the relationship between aerobic fitness and cognitive performance. *Brain Research Reviews, 52*(1), 119–130. doi:10.1016/j.brainresrev.2006.01.002

Fan, J., Gu, X., Guise, K.G., Liu, X., Fossella, J., Wang, H., & Posner, M.I. (2009). Testing the behavioral interaction and integration of attentional networks. *Brain and Cognition, 70*(2), 209–220. doi:10.1016/j.bandc.2009.02.002

de Felice, S., Hamilton, A.F.C., Ponari, M., & Vigliocco, G. (2023). Learning from others is good, with others is better: The role of social interaction in human acquisition of new knowledge. *Philosophical Transactions of the Royal Society of London, 378*(1870), 20210357. doi:10.1098/rstb.2021.0357

Flynn, R.M., & Richert, R.A. (2018). Cognitive, not physical, engagement in video gaming influences executive functioning. *Journal of Cognition and Development, 19*(1), 1–20. doi:10.1080/15248372.2017.1419246

Fransen, K., Boen, F., Vansteenkiste, M., Mertens, N., & Vande Broek, G. (2018). The power of competence support: The impact of coaches and athlete leaders on intrinsic motivation and performance. *Scandinavian Journal of Medicine & Science in Sports, 28*(2), 725–745. doi:10.1111/sms.12950

Fredrickson, B.L. (2004). The broaden-and-build theory of positive emotions. *Philosophical Transactions of the Royal Society of London, 359*(1449), 1367–1378. doi:10.1098/rstb.2004.1512

Furley, P., Schütz, L.M., & Wood, G. (2023). A critical review of research on executive functions in sport and exercise. *International Review of Sport and Exercise Psychology,* 1-29. doi:10.1080/1750984X.2023.2217437

Gallotta, M.C., Emerenziani, G.P., Franciosi, E., Meucci, M., Guidetti, L., & Baldari, C. (2015). Acute physical activity and delayed attention in primary school students. *Scandinavian Journal of Medicine & Science in Sports, 25*(3), 331–338. doi:10.1111/sms.12310

Gallotta, M.C., Guidetti, L., Franciosi, E., Emerenziani, G.P., Bonavolontà, V., Baldari, C., & Bonavolonta, V. (2012). Effects of varying type of exertion on children's attention capacity. *Medicine & Science in Sports & Exercise, 44*(3), 550–555. doi:10.1249/MSS.0b013e3182305552

Graham, J.D., Bremer, E., Fenesi, B., & Cairney, J. (2021). Examining the acute effects of classroom-based physical activity breaks on executive functioning in 11- to 14-year-old children: Single and additive moderation effects of physical fitness. *Frontiers in Pediatrics, 9*, 688251. doi:10.3389/fped.2021.688251

de Greeff, J. W., Bosker, R. J., Oosterlaan, J., Visscher, C., & Hartman, E. (2018). Effects of physical activity on executive functions, attention and academic performance in preadolescent children: A meta-analysis. *Journal of Science and Medicine in Sport, 21*(5), 501–507. doi:10.1016/j.jsams.2017.09.595

Guadagnoli, M.A., & Lee, T.D. (2004). Challenge point: A framework for conceptualizing the effects of various practice conditions in motor learning. *Journal of Motor Behavior, 36*(2), 212–224. doi:10.3200/JMBR.36.2.212-224

Hatch, L.M., Dring, K.J., Williams, R.A., Sunderland, C., Nevill, M.E., & Cooper, S.B. (2021). Effect of differing durations of high-intensity intermittent activity on cognitive function in adolescents. *International Journal of Environmental Research and Public Health, 18*(21). doi:10.3390/ijerph182111594

Herold, F., Hamacher, D., Schega, L., & Müller, N.G. (2018). Thinking while moving or moving while thinking - Concepts of motor-cognitive training for cognitive performance enhancement. *Frontiers in Aging Neuroscience, 10*, 228. doi:10.3389/fnagi.2018.00228

Herold, F., Müller, P., Gronwald, T., & Müller, N.G. (2019). Dose-response matters! – A perspective on the exercise prescription in exercise-cognition research. *Frontiers in Psychology, 10*, 2338. doi:10.3389/fpsyg.2019.02338

Herold, F., Törpel, A., Hamacher, D., Budde, H., Zou, L., Strobach, T., Müller, N.G., & Gronwald, T. (2021). Causes and consequences of interindividual response variability: A call to apply a more rigorous research design in acute exercise-cognition studies. *Frontiers in Physiology, 12*, 682891. doi:10.3389/fphys.2021.682891

Hillman, C.H., Logan, N.E., & Shigeta, T.T. (2019). A review of acute physical activity effects on brain and cognition in children. *Translational Journal of the ACSM, 4*(17), 132–136. doi:10.1249/TJX.0000000000000101

Hillman, C.H., McAuley, E., Erickson, K.I., Liu-Ambrose, T., & Kramer, A.F. (2019). On mindful and mindless physical activity and executive function: A response to Diamond and Ling (2016). *Developmental Cognitive Neuroscience, 37*, 100529. doi:10.1016/j.dcn.2018.01.006

Hohnemann, C., Schweig, S., Diestel, S., & Peifer, C. (2022). How feedback shapes flow experience in cognitive tasks: The role of locus of control and conscientiousness. *Personality and Individual Differences, 184*, 111166. doi:10.1016/j.paid.2021.111166

Howie, E.K., & Pate, R.R. (2012). Physical activity and academic achievement in children: A historical perspective. *Journal of Sport and Health Science, 1*(3), 160–169. doi:10.1016/j.jshs.2012.09.003

Howie, E.K., Schatz, J., & Pate, R.R. (2015). Acute effects of classroom exercise breaks on executive function and math performance: A dose-response study. *Research Quarterly for Exercise and Sport, 86*(3), 217–224. doi:10.1080/02701367.2015.1039892

Hwang, J., Hillman, C.H., Lee, I.M., Fernandez, A.M., & Lu, A.S. (2021). comparison of inhibitory control after acute bouts of exergaming between children with obesity and their normal-weight peers. *Games for Health Journal, 10*(1), 63–71. doi:10.1089/g4h.2020.0018

Ishihara, T., Drollette, E.S., Ludyga, S., Hillman, C.H., & Kamijo, K. (2021). Baseline cognitive performance moderates the effects of physical activity on executive functions in children. *Journal of Clinical Medicine, 9*(7), 2071. doi:10.3390/jcm9072071

Jäger, K., Schmidt, M., Conzelmann, A., & Roebers, C.M. (2014). Cognitive and physiological effects of an acute physical activity intervention in elementary school children. *Frontiers in Psychology, 5*, 71. doi:10.3389/fpsyg.2014.01473

Jäger, K., Schmidt, M., Conzelmann, A., & Roebers, C.M. (2015). The effects of qualitatively different acute physical activity interventions in real-world settings on executive functions in preadolescent children. *Mental Health and Physical Activity, 9*, 1–9. doi:10.1016/j.mhpa.2015.05.002

Jones, L., & Ekkekakis, P. (2019). Affect and prefrontal hemodynamics during exercise under immersive audiovisual stimulation: Improving the experience of exercise for overweight adults. *Journal of Sport and Health Science, 8*(4), 325–338. doi:10.1016/j.jshs.2019.03.003.

Kahneman, D. (1973). *Attention and effort*. Prentice-Hall.

Karr, J.E., Areshenkoff, C.N., Rast, P., Hofer, S.M., Iverson, G.L., & Garcia-Barrera, M.A. (2018). The unity and diversity of executive functions: A systematic review and re-analysis of latent variable studies. *Psychological Bulletin, 144*(11), 1147–1185. doi:10.1037/bul0000160

Kimura, D., Hosokawa, T., Ujikawa, T., & Ito, T. (2022). Effects of different exercise intensities on prefrontal activity during a dual task. *Scientific Reports, 12*(1), 13008. doi:10.1038/s41598-022-17172-5

Koziol, L.F., Budding, D., Andreasen, N., D'Arrigo, S., Bulgheroni, S., Imamizu, H., & Yamazaki, T. (2014). Consensus paper: The cerebellum's role in movement and cognition. *Cerebellum, 13*(1), 151–177. doi:10.1007/s12311-013-0511-x

Kristjánsson, Á., & Ásgeirsson, Á.G. (2019). Attentional priming: Recent insights and current controversies. *Current Opinion in Psychology, 29*, 71–75. doi:10.1016/j.copsyc.2018.11.013

Kruijne, W., & Meeter, M. (2015). The long and the short of priming in visual search. Attention, *Perception & Psychophysics, 77*(5), 1558–1573. doi:10.3758/s13414-015-0860-2

Lambourne, K., & Tomporowski, P.D. (2010). The effect of exercise-induced arousal on cognitive task performance: A meta-regression analysis. *Brain research, 1341*, 12–24. doi:10.1016/j.brainres.2010.03.091

Lämmle, L., Tittlbach, S., Oberger, J., Worth, A., & Bös, K. (2010). A two-level model of motor performance ability. *Journal of Exercise Science & Fitness, 8*(1), 41–49. doi:10.1016/S1728-869X(10)60006-8

Leahy, A.A., Mavilidi, M.F., Smith, J.J., Hillman, C.H., Eather, N., Barker, D., & Lubans, D.R. (2020). Review of high-intensity interval training for cognitive and mental health in youth. *Medicine and Science in Sports and Exercise, 52*(10), 2224–2234. doi:10.1249/MSS.0000000000002359

Lee, S., Kim, W., Park, T., & Peng, W. (2017). The psychological effects of playing exergames: A systematic review. *Cyberpsychology, Behavior and Social Networking, 20*(9), 513–532. doi:10.1089/cyber.2017.0183

Leone, L., & Pesce, C. (2017). From delivery to adoption of physical activity guidelines: Realist synthesis. *International Journal of Environmental Research and Public Health, 14*(10). doi:10.3390/ijerph14101193

Li, L., Zhang, J., Cao, M., Hu, W., Zhou, T., Huang, T., Chen, P., & Quan, M. (2020). The effect of chronic physical activity interventions on executive function in children aged 3-7 years: A meta-analysis. *Journal of Science and Medicine in Sport*, *23*(10), 949-954. doi:10.1016/j.jsams.2020.03.007

Li, Y., Wang, Y., Jin, X., Niu, D., Zhang, L., Jiang, S.Y., Ruan, H.D., & Ho, G.W. (2021). Sex differences in hemispheric lateralization of attentional networks. *Psychological Research, 85*(7), 2697–2709. doi:10.1007/s00426-020-01423-z

Liew, J. (2012). Effortful control, executive functions, and education: Bringing self-regulatory and social-emotional competencies to the table. *Child Development Perspectives, 6*(2), 105–111. doi:10.1111/j.1750-8606.2011.00196.x

Lopez-Gamundi, P., Yao, Y.W., Chong, T.J., Heekeren, H.R., Mas-Herrero, E., & Marco-Pallarés, J. (2021). The neural basis of effort valuation: A meta-analysis of functional magnetic resonance imaging studies. *Neuroscience and Biobehavioral Reviews, 131*, 1275–1287. doi:10.1016/j.neubiorev.2021.10.024

Lubans, D.R., Richards, J., Hillman, C., Faulkner, G., Beauchamp, M., Nilsson, M., Kelly, P., Smith, J., Raine, L., & Biddle, S. (2016). Physical activity for cognitive and mental health in youth: a systematic review of mechanisms. *Pediatrics, 138*(3), e20161642. doi:10.1542/peds.2016-1642

Lubans, D.R., Leahy, A.A., Mavilidi, M.F., & Valkenborghs, S.R. (2022). Physical activity, fitness, and executive functions in youth: Effects, moderators, and mechanisms. *Current Topics in Behavioral Neurosciences, 53*, 103–130. doi:10.1007/7854_2021_271

Ludyga, S., Gerber, M., Brand, S., Holsboer-Trachsler, E., & Puhse, U. (2016). Acute effects of moderate aerobic exercise on specific aspects of executive function in different age and fitness groups: A meta-analysis. *Psychophysiology, 53*(11), 1611–1626. doi:10.1111/psyp.12736

Ludyga, S., Gerber, M., Pühse, U., Looser, V.N., & Kamijo, K. (2020). Systematic review and meta-analysis investigating moderators of long-term effects of exercise on cognition in healthy individuals. *Nature Human Behaviour*, *4*(6), 603-612. doi:10.1038/s41562-020-0851-8

Lyons, E.J. (2015). Cultivating engagement and enjoyment in exergames using feedback, challenge, and rewards. *Games for Health Journal, 4*(1), 12–18. doi:10.1089/g4h.2014.0072

Macleod, J.W., Lawrence, M.A., McConnell, M.M., Eskes, G.A., Klein, R.M., & Shore, D.I. (2010). Appraising the ANT: Psychometric and theoretical considerations of the Attention Network Test. *Neuropsychology, 24*(5), 637–651. doi:10.1037/a0019803

Martin-Niedecken, A.L., Mahrer, A., Rogers, K., de Bruin, E.D, & Schättin, A. (2020). “HIIT” the ExerCube: Comparing the effectiveness of functional high-intensity interval training in conventional vs. exergame-based training. *Frontiers in Computer Science, 2*, 33. doi:10.3389/fcomp.2020.00033

Masini, A., Ceciliani, A., Dallolio, L., Gori, D., & Marini, S. (2022). Evaluation of feasibility, effectiveness, and sustainability of school-based physical activity "active break" interventions in pre-adolescent and adolescent students: A systematic review. *Canadian Journal of Public Health, 113*(5), 713–725. doi:10.17269/s41997-022-00652-6

Mavilidi, M.F., Pesce, C., Benzing, V., Schmidt, M., Paas, F., Okely, A.D., & Vazou, S. (2022). Meta-analysis of movement-based interventions to aid academic and behavioral outcomes: A taxonomy of relevance and integration. *Educational Research Review, 37*, 100478. doi:10.1016/j.edurev.2022.100478

McMorris, T. (2016). Developing the catecholamines hypothesis for the acute exercise-cognition interaction in humans: Lessons from animal studies. *Physiology & Behavior, 165*, 291–299. doi:10.1016/j.physbeh.2016.08.011

McMorris, T., & Hale, B.J. (2012). Differential effects of differing intensities of acute exercise on speed and accuracy of cognition: A meta-analytical investigation. *Brain and Cognition, 80*(3), 338–351. doi:10.1016/j.bandc.2012.09.001

Miyake, A., Friedman, N.P., Emerson, M.J., Witzki, A.H., Howerter, A., & Wager, T.D. (2000). The unity and diversity of executive functions and their contributions to complex "frontal lobe" tasks: A latent variable analysis. *Cognitive Psychology, 41*(1), 49–100. doi:10.1006/cogp.1999.0734

Moreau, D., & Chou, E. (2019). The acute effect of high-intensity exercise on executive function: A meta-analysis. *Perspectives on Psychological Science, 14*(5), 734–764. doi:10.1177/1745691619850568

Moreau, D., & Conway, A.R.A. (2014). The case for an ecological approach to cognitive training. *Trends in Cognitive Sciences, 18*(7), 334–336. doi:10.1016/j.tics.2014.03.009

Moriarty, T.A., Mermier, C., Kravitz, L., Gibson, A., Beltz, N., & Zuhl, M. (2019). Acute aerobic exercise based cognitive and motor priming: Practical applications and mechanisms. *Frontiers in Psychology, 10*, 2790. doi:10.3389/fpsyg.2019.02790

Neuenschwander, R., Röthlisberger, M., Cimeli, P., & Roebers, C.M. (2012). How do different aspects of self-regulation predict successful adaptation to school? *Journal of Experimental Child Psychology, 113*, 353–371. doi: 10.1016/j.jecp.2012.07.004

Paas, F., & Sweller, J. (2012). An evolutionary upgrade of cognitive load theory: Using the human motor system and collaboration to support the learning of complex cognitive tasks. *Educational Psychology Review, 24*(1), 27–45. doi:10.1007/s10648-011-9179-2

Paas, F., Tuovinen, J.E., Tabbers, H., & Van Gerven, P.W.M. (2003). Cognitive load measurement as a means to advance cognitive load theory. *Educational Psychologist, 38*(1), 63–71. doi:10.1207/S15326985EP3801_8

Paschen, L., Lehmann, T., Kehne, M., & Baumeister, J. (2019). Effects of acute physical exercise with low and high cognitive demands on executive functions in children: A systematic review. *Pediatric Exercise Science, 31*(3), 267–281. doi:10.1123/pes.2018-0215

Peifer, C., Schönfeld, P., Wolters, G., Aust, F., & Margraf, J. (2020). Well done! Effects of positive feedback on perceived self-efficacy, flow and performance in a mental arithmetic task. *Frontiers in Psychology, 11*, 1008. doi:10.3389/fpsyg.2020.01008

Perry, R.E., Finegood, E.D., Braren, S.H., & Blair, C. (2019). The social neuroendocrinology and development of executive functions. In O.C. Schultheiss & P.H. Mehta (Eds.), *Routledge international handbook of social neuroendocrinology* (pp. 530–543). Routledge.

Pesce, C. (2009). An integrated approach to the effect of acute and chronic exercise on cognition: The linked role of individual and task constraints. In T. McMorris, P.D. Tomporowski, & M. Audiffren (Eds.), *Exercise and cognitive function*. Wiley-Heinrich.

Pesce, C. (2012). Shifting the focus from quantitative to qualitative exercise characteristics in exercise and cognition research. *Journal of Sport & Exercise Psychology, 34*(6), 766–786. doi:10.1123/jsep.34.6.766

Pesce, C., Croce, R., Ben-Soussan, T.D., Vazou, S., McCullick, B., Tomporowski, P.D., & Horvat, M. (2016). Variability of practice as an interface between motor and cognitive development. *International Journal of Sport and Exercise Psychology,* 1–20. doi:10.1080/1612197X.2016.1223421

Pesce, C., Vazou, S., Benzing, V., Álvarez-Bueno, C., Anzeneder, S., Mavilidi, M.F., Leone, L., & Schmidt, M. (2021). Effects of chronic physical activity on cognition across the lifespan: a systematic meta-review of randomized controlled trials and realist synthesis of contextualized mechanisms. *International Review of Sport and Exercise Psychology*, 1–39. doi:10.1080/1750984X.2021.1929404

Petersen, S.E., & Posner, M.I. (2012). The attention system of the human brain: 20 years after. *Annual Review of Neuroscience, 35*, 73–89. doi:10.1146/annurev-neuro-062111-150525

Piepmeier, A.T., & Etnier, J.L. (2014). Brain-derived neurotrophic factor (BDNF) as a potential mechanism of the effects of acute exercise on cognitive performance. *Journal of Sport and Health Science, 4*(1), 14-23. doi:10.1016/j.jshs.2014.11.001

Poitras, V.J., Gray, C.E., Borghese, M.M., Carson, V., Chaput, J.P., Janssen, I., Katzmarzyk, P.T., Pate, R.R., Connor Gorber, S., Kho, M.E., Sampson, M., & Tremblay, M.S. (2016). Systematic review of the relationships between objectively measured physical activity and health indicators in school-aged children and youth. *Applied Physiology, Nutrition, and Metabolism, 41*(6), 197-239. doi:10.1139/apnm-2015-0663

Pontifex, M.B., McGowan, A.L., Chandler, M.C., Gwizdala, K.L., Parks, A.C., Fenn, K., & Kamijo, K. (2019). A primer on investigating the after effects of acute bouts of physical activity on cognition. *Psychology of Sport and Exercise, 40*, 1–22. doi:10.1016/j.psychsport.2018.08.015

Posner, M.I., & Rothbart, M.K. (2014). Attention to learning of school subjects. *Trends in Neuroscience and Education, 3*(1), 14–17. doi:10.1016/j.tine.2014.02.003

Roebers, C.M. (2017). Executive function and metacognition: Towards a unifying framework of cognitive self-regulation. *Developmental Review, 45*, 31–51. doi:10.1016/j.dr.2017.04.001

Roebers, C.M., Schmid, C., & Roderer, T. (2009). Metacognitive monitoring and control processes involved in primary school children's test performance. *British Journal of Educational Psychology, 79*(4), 749–767. doi:10.1348/978185409X429842

Ryan, R.M., & Deci, E.L. (2000). Intrinsic and extrinsic motivations: Classic definitions and new directions. *Contemporary Educational Psychology, 25*(1), 54–67. doi:10.1006/ceps.1999.1020

Sanders, A. F. (1983). Towards a model of stress and human performance. *Acta Psychologica, 53*, 61–97.

Schmidt, M., Benzing, V., & Kamer, M. (2016). Classroom-based physical activity breaks and children's attention: Cognitive engagement works! *Frontiers in Psychology, 7*, 1474. doi:10.3389/fpsyg.2016.01474

Schmidt, M., Egger, F., Anzeneder, S., & Benzing, V. (2021). Acute cognitively challenging physical activity to promote children’s cognition. In R. Bailey (Ed.), *ICSSPE perspectives. Physical activity and sport during the first ten years of life: Multidisciplinary perspectives* (pp. 141–155). Routledge.

Schmidt, M., Egger, F., Benzing, V., Jäger, K., Conzelmann, A., Roebers, C.M., & Pesce, C. (2017). Disentangling the relationship between children’s motor ability, executive function and academic achievement. *Plos One, 12*(8), e0182845. doi:10.1371/journal.pone.0182845

Serrien, D.J., Ivry, R.B., & Swinnen, S.P. (2007). The missing link between action and cognition. *Progress in Neurobiology, 82*(2), 95–107. doi:10.1016/j.pneurobio.2007.02.003

Simpson, T., Ellison, P., Carnegie, E., & Marchant, D. (2021). A systematic review of motivational and attentional variables on children’s fundamental movement skill development: the OPTIMAL theory. *International Review of Sport and Exercise Psychology, 14*(1), 312–358. doi:10.1080/1750984X.2020.1809007

Singh, A.S., Saliasi, E., van den Berg, V., Uijtdewilligen, L., de Groot, R.H.M., Jolles, J., Andersen, L.B. et al. (2019). Effects of physical activity interventions on cognitive and academic performance in children and adolescents: A novel combination of a systematic review and recommendations from an expert panel. *British Journal of Sports Medicine, 53*(10), 640–647. doi:10.1136/bjsports-2017-098136

Smid, C.R., Karbach, J., & Steinbeis, N. (2020). Toward a science of effective cognitive training. *Current Directions in Psychological Science, 29*(6), 531-537. doi: 10.1177/0963721420951599

Stanley, P.J. & Schutte, N.S. (2023). Merging the self-determination theory and the broaden and build theory through the nexus of positive affect: A macro theory of positive functioning. *New Ideas in Psychology, 68*, 100979. doi:10.1016/j.newideapsych.2022.100979

Stillman, C.M., Cohen, J., Lehman, M.E., & Erickson, K.I. (2016). Mediators of physical activity on neurocognitive function: A review at multiple levels of analysis. *Frontiers in Human Neuroscience, 10*, 626. doi:10.3389/fnhum.2016.00626

Stodden, D.F., Pesce, C., Zarrett, N., Tomporowski, P.D., Ben-Soussan, T.D., Brian, A., Abrams, T.C., & Weist, M.D. (2023). Holistic functioning from a developmental perspective: A new synthesis with a focus on a multi-tiered system support structure. *Clinical Child and Family Psychology Review, 26*(2), 343–361. doi:10.1007/s10567-023-00428-5

Sweetser, P., & Wyeth, P. (2005). GameFlow: A model for evaluating player enjoyment in games. *Computers in Entertainment, 3*(3), 3. doi:10.1145/1077246.1077253

Takacs, Z.K., & Kassai, R. (2019). The efficacy of different interventions to foster children's executive function skills: A series of meta-analyses. *Psychological Bulletin, 145*(7), 1-45. doi:10.1037/bul0000195

Terry, P.C., Karageorghis, C I., Curran, M.L., Martin, O.V., & Parsons-Smith, R.L. (2020). Effects of music in exercise and sport: A meta-analytic review. *Psychological Bulletin, 146*(2), 91–117. doi:10.1037/bul0000216

Themanson, J.R., Pontifex, M.B., & Hillman, C.H. (2008). Fitness and action monitoring: Evidence for improved cognitive flexibility in young adults. *Neuroscience, 157*(2), 319–328. doi:10.1016/j.neuroscience.2008.09.014

Tice, D.M., Baumeister, R.F., Shmueli, D., & Muraven, M. (2007). Restoring the self: Positive affect helps improve self-regulation following ego depletion. *Journal of Experimental Social Psychology, 43*(3), 379–384. doi: 10.1016/j.jesp.2006.05.007

Tomporowski, P.D., McCullick, B., & Pesce, C. (2015). *Enhancing children's cognition with physical activity games*. Human Kinetics.

Tomporowski, P.D., & Pesce, C. (2019). Exercise, sports, and performance arts benefit cognition via a common process. *Psychological Bulletin, 145*(9), 929–951. doi:10.1037/bul0000200 van den Berg, V., Saliasi, E., de Groot, R.H.M., Jolles, J., Chinapaw, M.J.M., & Singh, A.S. (2016). Physical activity in the school setting: Cognitive performance is not affected by three different types of acute exercise. *Frontiers in Psychology, 7*, 723. doi:10.3389/fpsyg.2016.00723

van den Berg, V., Saliasi, E., Jolles, J., de Groot, R.H.M., Chinapaw, M.J.M., & Singh, A.S. (2018). Exercise of varying durations: No acute effects on cognitive performance in adolescents. *Frontiers in Neuroscience, 12*, 672. doi:10.3389/fnins.2018.00672

van Stralen, M.M., Yıldırım, M., Wulp, A., te Velde, S.J., Verloigne, M., Doessegger, A., Androutsos, O., Kovács, É., Brug, J., & Chinapaw, M.J.M. (2014). Measured sedentary time and physical activity during the school day of European 10- to 12-year-old children: The ENERGY project. *Journal of Science and Medicine in Sport, 17*(2), 201–206. doi:10.1016/j.jsams.2013.04.019

Vazou, S., Pesce, C., Lakes, K., & Smiley-Oyen, A. (2019). More than one road leads to Rome: A narrative review and meta-analysis of physical activity intervention effects on cognition in youth. *International Journal of Sport and Exercise Psychology,* 1–26. doi:10.1080/1612197X.2016.1223423

Vazou, S., & Smiley-Oyen, A. (2014). Moving and academic learning are not antagonists: Acute effects on executive function and enjoyment. *Journal of Sport and Exercise Psychology, 36*(5), 474–485. doi:10.1123/jsep.2014-0035

Vella, S.A., Sutcliffe, J.T., Fernandez, D., Liddelow, C., Aidman, E., Teychenne, M., Smith, J.J., Swann, C., Rosenbaum, S., White, R.L., & Lubans, D.R. (2023). Context matters: A review of reviews examining the effects of contextual factors in physical activity interventions on mental health and wellbeing. *Mental Health and Physical Activity, 25*, 100520. doi:10.1016/j.mhpa.2023.100520

Verburgh, L., Königs, M., Scherder, E.J.A., & Oosterlaan, J. (2014). Physical exercise and executive functions in preadolescent children, adolescents and young adults: A meta-analysis. *British Journal of Sports Medicine, 48*(12), 973–979. doi:10.1136/bjsports-2012-091441

Viterbori, P., Usai, M.C., Traverso, L., & de Franchis, V. (2015). How preschool executive functioning predicts several aspects of math achievement in Grades 1 and 3: A longitudinal study. *Journal of Experimental Child Psychology, 140*, 38–55. doi:10.1016/j.jecp.2015.06.014

Voss, M.W., Vivar, C., Kramer, A.F., & van Praag, H. (2013). Bridging animal and human models of exercise-induced brain plasticity. *Trends in Cognitive Sciences, 17*(10), 525–544. doi: 10.1016/j.tics.2013.08.001

Wen, X., Yang, Y., & Wang, F. (2021). Influence of acute exercise on inhibitory control and working memory of children: A comparison between soccer, resistance, and coordinative exercises. *International Journal of Sport Psychology, 52,* 101–119. doi:10.7352/IJSP.2021.52.101

Wessinger, C.M., & Clapham, E. (2009). Cognitive Neuroscience: An Overview. In L.R. Squire (Ed.), *Encyclopedia of Neuroscience* (pp. 1117–1122). Elsevier.

Westbrook, A., Lamichhane, B., & Braver, T. (2019). The subjective value of cognitive effort is encoded by a domain-general valuation network. *The Journal of Neuroscience, 39*(20), 3934–3947. doi:10.1523/JNEUROSCI.3071-18.2019

Wilson, M. (2002). Six views of embodied cognition. Psychonomic Bulletin & Review, 9(4), 625–636. doi:10.3758/BF03196322

Wulf, G., & Lewthwaite, R. (2016). Optimizing performance through intrinsic motivation and attention for learning: The OPTIMAL theory of motor learning. Psychonomic Bulletin & Review, 23(5), 1382–1414. doi:10.3758/s13423-015-0999-9

Xue, Y., Yang, Y., & Huang, T. (2019). Effects of chronic exercise interventions on executive function among children and adolescents: A systematic review with meta-analysis. British Journal of Sports Medicine, 53(22), 1397–1404. doi:10.1136/bjsports-2018-099825

Zink, N., Lenartowicz, A., & Markett, S. (2021). A new era for executive function research: On the transition from centralized to distributed executive functioning. Neuroscience and Biobehavioral Reviews, 124, 235–244. doi:10.1016/j.neubiorev.2021.02.011

Acknowledgments

The present umbrella paper and the included publications are the result of fruitful teamwork. Therefore, I would like to express my sincere gratitude to all those who have made significant contributions to this work. First, I extend my heartfelt thanks to you, dear Mirko, for providing me with the opportunity to embark on this wonderful journey and discover the true meaning of "intrinsic" research interest. Thank you for your trust and unwavering (personal and professional) support throughout my entire doctoral journey. A special thanks goes to you, dear Valentin. During challenging times, you took on the role of a co-supervisor, and I am immensely grateful for that. I really appreciated our critical and constructive exchanges on all papers, joint projects, and seminars. Above all, you continuously challenged and motivated me to step out of my comfort zone!

Furthermore, I express my gratitude to my mentor Achim and department lecturer André for their precious advice, active co-thinking, and open-door policy. I consider myself fortunate to have you, Cäcilia, on this journey with me, carrying this project forward into new horizons. Thank you for your support and insightful feedback. A heartfelt thanks goes also to the entire sport pedagogy team and our colleagues from sport psychology. I am grateful for our personal and scientific enriching exchanges. A special mention goes to you, dear Jürg, for your substantial contribution and determination in resolving the "statistical dilemma" of *study 3*. Furthermore, I would like to express my gratitude to Claudia Voelcker-Rehage. Thank you very much for the time you dedicated to me.

On a personal level, this research journey is just one part of a larger journey that led me to move to Switzerland and establish roots here. None of this would have been possible without the unconditional love of my parents, especially my mother. I am immensely grateful for your unwavering support and wise advice. I also extend my heartfelt thanks to you, Elias, for always being there for me and patiently supporting me, even during the most stressful times. Lastly, I want to extend my thanks to my close friends, Olivia and Iris, who accompanied me on this journey. Your encouragement has empowered me to purpose my own path. Thank you all!

Supplementary material

I

Anzeneder, **S.**, Zehnder, C., Martin-Niedecken, A. L., Schmidt, M., & Benzing, V. (2023a). Acute exercise and children's cognitive functioning: What is the optimal dose of cognitive challenge? *Psychology of Sport and Exercise, 66*, 102404. https://doi.org/10.1016/j.psychsport.2023.102404

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Psychology of Sport & Exercise 66 (2023) 102404

Contents lists available at ScienceDirect

Psychology of Sport & Exercise

journal homepage: www.elsevier.com/locate/psychsport

Acute exercise and children's cognitive functioning: What is the optimal dose of cognitive challenge?☆

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ARTICLE INFO

Keywords:
Physical activity
Exergaming
Cognitive engagement
Executive function
Attention network task

ABSTRACT

Acute bouts of exercise have the potential to benefit children's cognition. Inconsistent evidence on the role of qualitative exercise task characteristics calls for further investigation of the cognitive challenge level in exercise. Thus, the study aim was to investigate which "dose" of cognitive challenge in acute exercise benefits children's cognition, also exploring the moderating role of individual characteristics. In a within-subject experimental design, 103 children ($M_{age} = 11.1$, $SD = 0.9$, 48% female) participated weekly in one of three 15-min exergames followed by an Attention Network task. Exergame sessions were designed to keep physical intensity constant (65% HR_{max}) and to have different cognitive challenge levels (low, mid, high; adapted to the ongoing individual performance). ANOVAs performed on variables that reflect the individual functioning of attention networks revealed a significant effect of cognitive challenge on executive control efficiency (reaction time performances; $p = .014$, $\eta_p^2 = .08$), with better performances after the high-challenge condition compared to lower ones ($ps < .015$), whereas alerting and orienting were unaffected by cognitive challenge ($ps > .05$). ANOVAs performed on variables that reflect the interactive functioning of attention networks revealed that biological sex moderated cognitive challenge effects. For males only, the cognitive challenge level influenced the interactive functioning of executive control and orienting networks ($p = .004$; $\eta_p^2 = .07$). Results suggest that an individualized and adaptive cognitively high-challenging bout of exercise is more beneficial to children's executive control than less challenging ones. For males, the cognitive challenge in an acute bout seems beneficial to maintain executive control efficiency also when spatial attention resources cannot be validly allocated in advance. Results are interpreted referring to the cognitive stimulation hypothesis and arousal theory.

1. Introduction

A wide evidence base supports the transient effects of acute exercise (i.e., a single bout of exercise[1]) on children and adolescents' executive functions (EFs; Chang et al., 2012; de Greeff, Bosker, Oosterlaan, Visscher, & Hartman, 2018; Donnelly et al., 2016). EFs are a set of higher-level cognitive processes underlying the organization and control of adaptive and goal-directed behavior (Diamond, 2013). Among core EFs, inhibition includes the ability to suppress or resist automatic responses (response inhibition), suppress thoughts and memories (cognitive inhibition), and exert control over interference (executive interference control; Diamond, 2013). The latter is conceptually placed at the intersection between the broad constructs of EFs and attention. Executive control is one of three independent yet interacting attention networks, along with alerting (achieving and maintaining an alert state) and orienting (selecting information from sensory input; Petersen & Posner, 2012).

Regarding after-effects of acute exercise on executive control in children and adolescents, meta-analytic findings show positive effects, with ES ranging from 0.28 to 0.57 (de Greeff et al., 2018; Ludyga, Gerber, Brand, Holsboer-Trachsler, & Puhse, 2016; Verburgh, Königs, Scherder, & Oosterlaan, 2014). To better understand the underlying

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[1] In 'exercise and cognition' research, the meaning of the term 'exercise' has been expanded to encompass any specific form of physical activity that is planned, structured, and purposive to maintain or improve outcomes in different domains (e.g., physical, cognitive; Herold et al., 2021).

https://doi.org/10.1016/j.psychsport.2023.102404
Received 28 July 2022; Received in revised form 26 November 2022; Accepted 8 February 2023
Available online 10 February 2023
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mechanisms of these effects, it is important to consider how executive control interacts with other attention networks (alerting and orienting). However, the available evidence of acute exercise effects on alerting and orienting networks is limited, with studies investigating only the individual functioning of these networks in children (van den Berg et al., 2018) and adults (Chang, Pesce, Chiang, Kuo, & Fong, 2015), without considering their interactive functioning with executive control. Although positive results on EFs generally seem consistent, there is considerable heterogeneity in the magnitude of effects (Lubans, Leahy, Mavilidi, & Valkenborghs, 2022). As a result, research increasingly focused on a variety of quantitative and qualitative exercise task characteristics that may moderate effects on EFs.

One of the qualitative characteristics of exercise most widely discussed in recent years as having an impact on children's EFs is cognitive challenge (or demand) inherent in motor tasks (Best, 2010; Pesce, 2012; Tomporowski, McCullick, Pendleton, & Pesce, 2015). Cognitive challenge is thought to induce cognitive engagement, which is defined as the degree to which the allocation of attentional resources and cognitive effort is needed to master complex tasks (Pesce, 2012). The empirical evidence concerning the beneficial effects of cognitive challenge in acute exercise on children's EFs is, however, limited and inconsistent (Paschen, Lehmann, Kehne, & Baumeister, 2019). Compared to less cognitively challenging acute bouts of exercise, some studies revealed positive effects in favor of the more challenging conditions (Benzing, Heinks, Eggenberger, & Schmidt, 2016; Budde, Voelcker-Rehage, Pietraßyk-Kendziorra, Ribeiro, & Tidow, 2008; Flynn & Richert, 2018; Jäger, Schmidt, Conzelmann, & Roebers, 2014; Schmidt, Benzing, & Kamer, 2016), while others found no difference (Bedard, Bremer, Graham, Chirico, & Cairney, 2021; Best, 2012; Jäger, Schmidt, Conzelmann, & Roebers, 2015; van den Berg et al., 2016; Wen, Yang, & Wang, 2021), or even detrimental effects (Egger, Conzelmann, & Schmidt, 2018; Gallotta et al., 2012, 2015). Inconsistent findings may be due to differences in exercise characteristics (e.g., applied durations, intensities, modalities), interacting with individual characteristics (e.g., developmental stage, biological sex, skill level, previous experience; Schmidt, Egger, Anzeneder, & Benzing, 2021). Therefore, systematic investigations of dose-response relations among cognitive challenge levels and children's EFs are needed (Schmidt et al., 2021).

Thus, the rationale behind the present study has both practical and theoretical relevance. From a practical point of view, cognitively challenging bouts of exercise are inherently varying and therefore more suitable for children's preferences than bouts with low cognitive demands (Paschen et al., 2019). Most importantly, from a theoretical point of view, the assumptions of the cognitive stimulation hypothesis on the effect of cognitive engagement on EFs can be investigated. According to this hypothesis, a cognitively challenging and physically active task performance activates similar frontal-dependent circuitries as sedentary EFs tasks (Best, 2010; Tomporowski et al., 2015), resulting in more efficient executive functioning that continues after the cessation of the activity (Budde et al., 2008; Pesce, 2012). The activation is expected to be strongest when the task is novel, requires concentration, and the response is unpredictable and fast (Best, 2010). However, only studies in which the cognitive challenge level is systematically manipulated and individually adapted to match children's skill level, while exercise modality and physical exercise intensity are held constant, can provide insights on the assumptions of the cognitive stimulation hypothesis.

One tool that allows for the controlled manipulation and individualization of both physical and cognitive challenges of exercise is exergaming. Exergaming (or active video gaming) is a portmanteau of "exercising" and "gaming" (Benzing & Schmidt, 2018). It has been shown that exergaming can be a motivating, physically and cognitively challenging form of acute exercise for children and adolescents (Benzing et al., 2016; Best, 2012; Ketelhut, Röglin, Martin-Niedecken, Nigg, & Ketelhut, 2022). To date, only a few studies have investigated the effect of cognitive challenge in acute exergaming on children's and adolescents' EFs (Benzing et al., 2016; Best, 2012; Flynn & Richert, 2018). While in two studies, cognitively challenging exergaming was found to be superior to a less challenging exergaming (Benzing et al., 2016) or aerobic exercise (Flynn & Richert, 2018), another study found physical exercise intensity and not the level of cognitive challenge to be the performance determinant (Best, 2012). Diverging acute study results on the effect of cognitive challenge within exergaming depict the need to consider specific aspects in acute cognitively challenging exercise studies. (1) First, while well-designed exergaming studies controlled for physical exercise intensity, perceived exertion, and other potential confounders (e.g., pleasure), they used completely different exercise types (Best, 2012; Flynn & Richert, 2018) or different exergames to manipulate cognitive challenge (Benzing et al., 2016). Thus, it is likely that the experimental conditions did not only differ in cognitive challenge but also in physical task demands, not allowing to disentangle the individual and combined effects of cognitive and physical challenges on EFs. (2) Second, previous studies did not adapt the dosage of cognitive challenge within the acute exercise to the individual skill level. Analogously to what has been proposed for the individualization of quantitative characteristics (i.e., intensity, duration; Herold, Müller, Gronwald, & Müller, 2019, 2021), it seems beneficial to individualize also the cognitive demands of the exercise task to the respective skill level.

Thus, the aim of the current study was threefold. (1) The primary aim was to investigate which "dose" of cognitive challenge in an acute exergaming-based exercise benefits children's executive control the most. (2) The second aim was to extend the focus from the most commonly studied executive control to incorporate other attention networks (alerting and orienting, including their interactive functioning). (3) The third aim was to explore whether individual characteristics (e.g., age, sex, need for cognition, fitness) interact with task constraints (cognitive challenge levels) to determine an optimal challenge point.

Our hypotheses were: (1) A higher cognitive challenge should elicit larger executive control gains, in line with the cognitive stimulation hypothesis. (2) Considering that acute exercise studies addressing after-effects on alerting and orienting are limited and inconsistent (Chang, Pesce, et al., 2015; van den Berg et al., 2018) and none investigated the interaction among attention networks, no a priori hypothesis was stated. Since, however, attention network literature shows that executive control efficiency is worse when attention cannot be alerted or spatially oriented in advance (Fan et al., 2009), we explored if the level of cognitive challenge in acute exercise influenced the interactive functioning of executive control with other attention networks. (3) Given the limited evidence on the moderating role of individual characteristics regarding the effects of acute cognitively challenging exercise, no a priori hypothesis was formulated.

2. Methods

This trial is part of the project "School-based physical activity and children's cognitive functioning: The quest for theory-driven intervention". The project aims to investigate the effects of qualitative and quantitative characteristics of designed school-based physical activity on children's cognitive functions. The project was registered in the German Clinical Trials Registry (registration number: DRKS00023254). The cantonal ethics committee approved the study protocol (number: 2020-00624), which adhered to the latest declaration of Helsinki.

2.1. Participants

A total of 103 children, aged 10–13 years ($M = 11.1$, $SD = 0.9$; 48% female), were recruited from five primary schools in the canton of Bern (Switzerland). The legal guardians of all children provided informed written consent and children agreed to participate. The exclusion criteria were any neurological, developmental, or medical condition that would affect the subjects' integrity or study results. To determine sample size, we conducted a simulated power analysis using the SuperPower Shiny app (https://shiny.ieis.tue.nl/anova_power/). We defined a within-subjects design with three cognitive challenge conditions and estimated effects based on previous exergaming evidence (Benzing et al., 2016; Best, 2012; Flynn & Richert, 2018) with alpha error probability = .05 and correlation between the repeated measures $r = 0.61$. We assumed that children's executive control performance would be faster after the high-challenging condition ($M = 135$, $SD = 80$), compared to the mid ($M = 155$, $SD = 80$) and low one ($M = 175$, $SD = 80$). To satisfy counterbalancing requirements, we tested the power of $N = 100$ participants. Using 2000 simulations, results showed that a power of 99% for repeated measures ANOVAs and more interestingly a power of 80% for *t*-test comparisons among cognitive challenge conditions would be favorable to detect effects.

We continuously recruited participants. Of the 110 participants recruited, two were injured during the study period and five were identified as multivariate outliers based on the Mahalanobis distance ($p < .001$), and were therefore excluded. Due to technical problems with the tablets used for ANT assessments (SurfTab 10.1, TrekStor GmgH, Lorsch, Germany), there was some loss of data (4.7%). Since the MCAR test has led to a non-significant result ($p = .662$), the missing values were imputed using the expectation-maximization algorithm. Participants' background variables are presented in Table 1.

2.2. Design and procedures

In the current within-subject crossover design study with counterbalanced order of experimental conditions (six possible permutations), the cognitive challenge of an acute bout of exergaming was manipulated to be low, mid, or high (whereby each level was individually adapted according to the ongoing individual performance).

The study was conducted over four weeks. During the first study week, data were collected in two visits. On the first visit, children filled out a questionnaire about their background characteristics [age, biological sex, height, weight, socioeconomic status (Torsheim et al., 2016), pubertal developmental status (Watzlawik, 2009), habitual physical activity (Kowalski, Crocker, & Faulkner, 1997), need for cognition (Preckel, 2014), need for affect (Appel, Gnambs, & Maio, 2012), and previous videogame expertise]. Subsequently, they performed a 20-m Shuttle Run test (Léger, Mercier, Gadoury, & Lambert, 1988) to assess their maximum heart rate (HR) and fitness level. Acceptable reliability and validity were demonstrated for background variables; only the videogame expertise questionnaire was self-developed for the current study (for a detailed description of background variables see Appendix A). In the second visit, children participated in a procedure familiarization session. Each child completed a specifically developed tutorial for exergaming tasks, in which each movement was explained and the exergame continued only when movements were carried out correctly, followed by a 3-min regular version of the exergame. The attentional testing was familiarized using the practice block of the Inquisit 5 Millisecond Software (for details, see 'Cognitive measures'). Between the second and the fourth week, children played one exergaming session per week, blinded to the level of cognitive challenge. Before (T_0), during (T_1 and T_2), and after (T_3) exergaming, manipulation check and control variables, including perceived physical exertion, cognitive engagement, pleasure, arousal and stress were collected (see 'Manipulation check' and 'Control variables' sections). During the exergaming task, children wore HR-monitoring devices. In total, each visit lasted about 35 min, including a short assessment break before exergaming (T_0), 2 min warm-up, 15 min of exergaming intermitted by one short assessment break every 5 min of activity (T_1, T_2, T_3), a water break after the exergaming, and the subsequent cognitive functioning assessment with ANT-R (Fan et al., 2009). The experimental protocol of the individual weekly sessions can be seen in Figure 1. Children were tested one after another so that when the first child started the attentional testing, the second one started the exergaming. Per day, a maximum of 10 children were tested. Testing and evaluation were conducted by the first author together with a team of trained research assistants and sport science students.

Table 1
Participants' background variables.

Background variables	*M* (*SD*)
Age (years)	11.1 (0.9)
Biological sex (% female)	48%
Socioeconomic status [2–14]	8.4 (1.3)
Body mass index (kg/m^2)	18.1 (3.1)
Pubertal developmental status [3–12]	4.7 (2.0)
Habitual physical activity [1–5]	2.6 (0.6)
VO_2max (ml/kg/min)	50.9 (5.2)
Videogame expertise [1–7]	3.8 (2.5)
Need for cognition [19–95]	57.7 (12.5)
Need for affect [-30–30]	6.7 (7.4)

2.3. Intervention and experimental conditions

Exergaming sessions took place in the school during school hours and were performed individually, once weekly, at the same time and day each week. The intervention consisted of a modified, screen-based version of the exergame Sphery Racer, played within a 3 × 2 m playing field (Martin-Niedecken, Rogers, Turmo Vidal, Mekler, & Márquez Segura, 2019, 2020). During the exergame session, participants wore four motion-based trackers (HTC Vive tracking sensors, Vive, Seattle, United States) attached to their wrists and ankles as well as an HR sensor (Polar Team2 straps and transmitters; Polar Electro Oy, Kempele, Finland) to constantly track their movements and body position, and their HR, respectively. The physical intensity was held constant during the session at 65% HR_{max}. Participants were projected directly into the virtual reality on a screen by integrated cameras and were taken by the game on a rapid sci-fi-themed underwater race. They navigated an avatar and passed various colored gates. Each gate requested a specific functional workout movement and/or cognitive task. Jumps, squats, skipping, and deep lunges were used to maintain the HR constant (50% of total movements). Punches and catching sideway points were used to manipulate the cognitive challenge (50% of total movements). Exergaming tasks were designed to mirror attentional allocation processes involved in the ANT paradigm. The tasks included anticipatory cues that alerted and oriented attention, and targets to be responded to with movement actions while ignoring distracting stimuli (for exergaming tasks see description and video in Appendix B and D). The level of cognitive challenge for each condition was predefined by an ascending number of distracting stimuli (low: 5–15%, mid: 20–35%, high: 40–60%) and misleading cues (low: 1–5%, mid: 7–12%, high: 13–19%) which preceded punches and catching sideway points movements. Within each condition, the level of cognitive challenge was constantly adapted to the ongoing individual performance (within the ranges mentioned above of distracting stimuli and misleading cues). The exergaming task was rendered easier or more difficult if the participant made more or less than three errors in 8 min, 1 min, or 30 s in the low-, mid-, and high-challenge conditions, respectively.

Supplementary video related to this article can be found at http://doi.org/10.1016/j.psychsport.2023.102404

2.4. Manipulation check

Several variables were assessed to test whether experimental manipulation had succeeded (see Figure 1). PolarTeam2 belts and transmitters (Polar Electro Oy, Kempele, Finland) were used to measure children's HR during exergaming (measurement every 3 s) and to adjust the physical intensity at 65% HR_{max}. In addition, the *perceived physical exertion* (RPE) was measured using the Borg RPE scale for perceived physical exertion (Borg, 1982). Evidence for acceptable reliability and

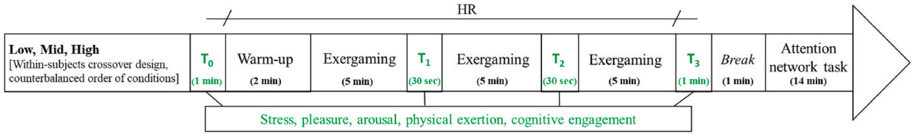


Figure 1. Experimental protocol of the weekly sessions.
Note. T_0 = before exergaming (pre); T_1 = 5 min exergaming; T_2 = 10 min exergaming; T_3 = after exergaming (post).

validity of the Borg RPE scale in preadolescents has been provided (Lamb, 1996). To determine children's *cognitive engagement* during exergaming, the Borg RPE scale was adapted to ask for the perceived cognitive engagement (RCE) of the activity. The question they had to answer was "How exhausting was the previous activity for your brain?". This adapted version is not a validated instrument but proved to be feasible with children and adolescents and sensitive to detect changes in cognitive engagement among intervention conditions (Benzing et al., 2016; Egger et al., 2018; Schmidt et al., 2016).

2.5. Control variables

Pleasure, arousal, and perceived stress were assessed using the single-item pictorial Self-Assessment-Manikin scale (see Figure 1). Evidence for an acceptable reliability and validity of the scale has been proven (Bradley & Lang, 1994).

2.6. Cognitive measures

A child-adapted version of the Attention Network Task (ANT-R; Fan et al., 2009) was used on Inquisit 5 (Millisecond Software, Seattle, WA) to assess the efficiency of: (a) the *executive control* (primary outcome), (b) *alerting* and *orienting networks*, as well as (c) *the interactive functioning of executive control with alerting and orienting networks*. For the primary outcome, retest reliability ranging from 0.61 to 0.71 has been shown (Macleod et al., 2010).

To capture the functioning of attention network systems, the test combines the Attention cueing paradigm (Petersen & Posner, 2012), that assesses alerting and orienting, and the Flanker task (Eriksen & Eriksen, 1974), that assesses executive control. There are four cue conditions: no cue, double cue, valid spatial cue, and invalid spatial cue; and two congruency conditions: a central target arrow surrounded by congruent (>> > > > or < < < < <) or incongruent (>> < > > or < < > < <) lateral flanker arrows. Each trial begins with a central fixation cross, followed by no cue, a double cue informing that a target will occur soon, or a single spatial cue informing on the probable location of the upcoming target. A valid spatial cue indicates the location where a subsequent target will appear. An invalid spatial cue indicates the opposite location. Subsequently, a congruent or incongruent flanker condition appears. Children's task is to identify the direction of the center arrow by pressing a right or left button while ignoring the lateral flanker arrows. Reaction times (RTs) and response accuracy are recorded. The task comprises two blocks of 72 trials (each bock with 12 no cue, 12 double cue, 36 valid spatial, and 12 invalid spatial trials) and lasts 14 min, including a 1-min break between the blocks. Responses with RTs faster than 200 ms or longer than 1700 ms were excluded automatically by the program (Fan, McCandliss, Sommer, Raz, & Posner, 2002). Further details on the task parameters and cue-target interval timing can be found elsewhere (Fan et al., 2009). Each attention system performance is computed as a difference value of RTs and accuracy.

- *Executive control* (flanker effect) is calculated as [incongruent – congruent trials]. A smaller value for the RT difference and a smaller negative value for the accuracy difference reflect a better efficiency, because children can better inhibit the interference of incongruent flankers.
- *Alerting* is calculated as [no cue – double cue trials]. A larger value for the RT difference and a larger negative value for the accuracy difference reflect the benefit in speed/accuracy elicited by an alerting cue.
- *Orienting* involves engaging attention at a validly cued location [double cue – valid spatial cue trials] and disengaging attention from an invalidly cued location [invalid spatial cue – double cue trials]. A larger RT difference and a larger negative value for the accuracy difference reflect the benefit in speed/accuracy elicited by a valid spatial cue, and/or the cost elicited by an invalid spatial cue.

The interactive function of the three attention networks is assessed as the effect of alerting or orienting on executive control (flanker effect). It is measured as the difference of flanker effect under different cue conditions.

- The *effect of alerting on executive control* is calculated as [(no cue trials with incongruent flanker – no cue trials with congruent flanker) – (double cue trials with incongruent flanker – double cue trials with congruent flanker)]. A negative value indicates a negative impact of alerting on executive control.
- The *effect of orienting on executive control* is composed of the effects of *engaging* and *disengaging* attention on executive control. The effect of *engaging* is calculated as [(double cue trials with incongruent flanker – double cue trials with congruent flanker) – (spatial valid cue trials with incongruent flanker – spatial valid cue trials with congruent flanker)]. The effect of *disengaging* is calculated as [(spatial invalid cue trials with incongruent flanker – spatial invalid cue trials with congruent flanker) – (double cue trials with incongruent flanker – double cue trials with congruent flanker)]. For *engaging*, a positive value indicates the beneficial effect of validly oriented attention on executive control. Instead, for *disengaging*, a positive value indicates the cost of invalidly oriented attention.

2.7. Statistical analyses

All analyses were performed using SPSS version 27.0 (SPSS Inc., Chicago, IL, USA). Preliminary analyses were run using repeated measures ANOVAs for the comparison of manipulation check (RPE, RCE) and control variables (pleasure, arousal, stress) among cognitive challenge conditions (low, mid, high) over exergaming time [pre (T_0), during (mean of T_1, T_2), and post (T_3)]. Post-hoc Bonferroni adjusted pairwise comparisons were reported for the cognitive challenge effect of interest. A further ANOVA was run to compare HR average among cognitive challenge conditions (low, mid, high).

To analyze the effect of the cognitive challenge level on attention network performances, a 3 (cognitive challenge level) × 4 (cue conditions) × 2 (flanker conditions) repeated measures ANOVA was performed separately for RTs and response accuracy. In the case of significant interactions, RT and accuracy differences were computed by subtracting cue and flanker conditions pairwise in a theory-driven manner (see 'Cognitive measures' section) to limit the amount of post-hoc comparisons and inflated risk of type II error. Thus, these difference values were used to contrast the cognitive challenge levels of interest using post-hoc Bonferroni adjusted pairwise comparisons.

To explore the role of individual characteristics on the cognitive challenge effects on attention networks, continuous individual background variables were first entered as covariates in a 3 (cognitive challenge level) × 4 (cue conditions) × 2 (flanker conditions) repeated measures ANCOVA. In the case of significant interactions of a covariate with the cognitive challenge factor, that variable was dichotomized and included as a categorical moderator in a subsequent ANOVA. The dichotomous sex variable was directly entered in the subsequent ANOVA as a moderator. In the case of significant interactions, including potential moderators, performances after the three cognitive challenge conditions were contrasted using the above-mentioned RT and accuracy difference values separately for the levels of the moderator variable.

For all analyses, median RTs were used because of the disproportional contribution of outliers in mean RTs for different participants and due to the non-normal distribution of RTs. All analyses were also performed on mean RTs, with and without the five multivariate outliers. Results depict median RTs with multivariate outliers excluded. The significance level was set at $p < .05$ for all analyses, and η_p^2 was reported as an effect size estimation.

3. Results

3.1. Manipulation check

Descriptive statistics of manipulation check variables among time points (pre, during, post) and cognitive challenge conditions (low, mid, high) are presented in Appendix C. The ANOVA revealed a significant effect of time (pre, during, post), cognitive challenge (low, mid, high), and their interaction on RPE [Time: $F(2, 101) = 152.63$, $p < .001$, $\eta_p^2 = .75$; Cognitive challenge: $F(2, 101) = 4.02$, $p < .021$, $\eta_p^2 = .07$; Cognitive challenge × Time: $F(4, 99) = 2.48$, $p = .049$, $\eta_p^2 = .09$] and RCE [Time: $F(2, 101) = 94.48$, $p < .001$, $\eta_p^2 = .65$; Cognitive challenge: $F(2, 101) = 10.21$, $p < .001$, $\eta_p^2 = .17$; Cognitive challenge × Time: $F(4, 99) = 2.37$, $p = .058$, $\eta_p^2 = .09$]. As concerns the cognitive challenge effect of interest, Bonferroni adjusted pairwise comparisons showed that the high-challenge condition was perceived as the most physically effortful (high vs. mid: $p = .048$, $\eta_p^2 = .03$; high vs. low: $p = .091$, $\eta_p^2 = .02$) and cognitively engaging (high vs. low: $p < .001$, $\eta_p^2 = .07$; high vs. mid: $p = .045$, $\eta_p^2 = .03$), whereas the low- and mid-challenge conditions were perceived as equally demanding ($ps > .256$, $\eta_{ps}^2 < .02$; see Appendix C). However, the difference in RPE among conditions was not paralleled by objective HR data ($p = .319$; $\eta_p^2 = .02$), which instead confirmed the intended similarity of physical challenge across conditions.

3.2. Control variables

Descriptive statistics of control variables among time points (pre, during, post) and cognitive challenge conditions (low, mid, high) are presented in Appendix C. The ANOVA revealed a significant effect of time (pre, during, post), cognitive challenge (low, mid, high), and their interaction on pleasure [Time: $F(2, 101) = 10.52$, $p < .001$, $\eta_p^2 = .17$; Cognitive challenge: $F(2, 101) = 8.77$, $p < .001$, $\eta_p^2 = .15$; Cognitive challenge × Time: $F(4,99) = 5.47$, $p = .001$, $\eta_p^2 = .18$], arousal [Time: $F(2, 101) = 20.99$, $p < .001$, $\eta_p^2 = .29$; Cognitive challenge: $F(2, 101) = 3.37$, $p = .038$, $\eta_p^2 = .06$; Cognitive challenge × Time: $F(4,99) = 3.08$, $p = .019$, $\eta_p^2 = .11$], and stress [Time: $F(2, 101) = 31.19$, $p < .001$, $\eta_p^2 = .38$; Cognitive challenge: $F(2, 101) = 4.76$, $p = .011$, $\eta_p^2 = .09$; Cognitive challenge × Time: $F(4,99) = 1.16$, $p = .34$, $\eta_p^2 = .05$]. As concerns the cognitive challenge effect of interest, Bonferroni adjusted pairwise comparisons showed that the high-challenge condition was perceived as the least pleasant (high vs. low: $p < .001$, $\eta_p^2 = .04$; high vs. mid: $p = .006$, $\eta_p^2 = .02$) and arousing (high vs. mid: $p = .031$, $\eta_p^2 = .02$; high vs. low: $p = .780$, $\eta_p^2 = .03$), and most stressful (high vs. low: $p = .009$, $\eta_p^2 = .02$; high vs. mid: $p = .200$; $\eta_p^2 = .02$), even though with limited (small to medium) effect sizes (see Appendix C).

3.3. Cognitive measures

3.3.1. Cognitive challenge effects on executive control, alerting, orienting, and their interaction

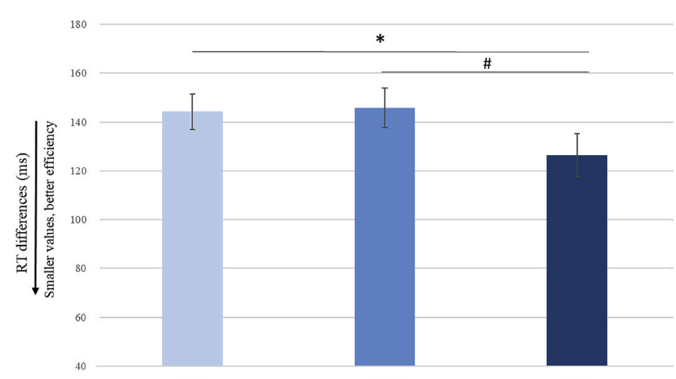
The first ANOVA on RTs revealed the classic Cue- [$F(3, 100) = 355.11$, $p < .001$, $\eta_p^2 = .91$], Flanker- [$F(1, 102) = 372.13$, $p < .001$, $\eta_p^2 = .79$] and Cue × Flanker effects [$F(3, 100) = 41.98$, $p < .001$, $\eta_p^2 = .56$]. These effects are well known in the literature (Fan et al., 2009).

Regarding the primary study aim, a significant Cognitive challenge × Flanker interaction with a medium effect emerged [$F(2, 100) = 4.46$, $p = .014$, $\eta_p^2 = .08$]. This interaction effect shows that the level of cognitive challenge influenced the subsequent efficiency of the executive control network (Figure 2). Post-hoc Bonferroni adjusted pairwise comparisons revealed faster RTs after the high-challenge condition, compared to the low ($p = .045$, $\eta_p^2 = .01$) and mid ones ($p = .011$, $\eta_p^2 = .02$), which in turn did not differ ($p = 1.00$, $\eta_p^2 = .00$). There were no cognitive challenge effects for accuracy ($p = .754$, $\eta_p^2 = .01$).

Concerning the second study aim, no effects of cognitive challenge emerged, in the whole sample, for alerting, orienting, or their interaction with executive control ($ps > .05$, $\eta_{ps}^2 < .01$ for both RTs and accuracy data).

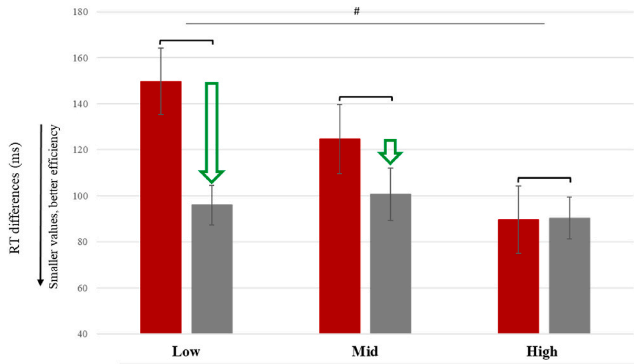
3.3.2. Moderating role of individual characteristics

Concerning the third study aim, ANCOVAs revealed no significant interaction effects of cognitive challenge with age, socio-economic, weight and pubertal status, habitual physical activity level, VO_2max, videogame expertise, need for cognition or need for affect ($ps > .05$, $\eta_{ps}^2 < .03$). A subsequent repeated measures ANOVA on RTs with biological sex as a potential moderator showed a Cognitive challenge × Flanker × Sex interaction with a small to medium effect [$F(2, 100) = 2.50$, $p = .087$, $\eta_p^2 = .05$], as well as a significant Cognitive challenge × Flanker × Cue × Sex interaction with a medium to high effect [$F(6, 96) = 2.33$, $p = .038$, $\eta_p^2 = .13$]. Subsequent ANOVAs were run on RT differences that reflect the flanker effect under different cue conditions (see 'Cognitive measure' section), separately for males and females. Significant differences for cognitive challenge were found only in males and only for the RT differences reflecting the interactive functioning of executive control (flanker effect) with orienting (spatial attention engagement) ($p = .001$, $\eta_p^2 = .22$). Post-hoc Bonferroni adjusted pairwise comparisons revealed a significant difference between the high- and low-challenge conditions ($p = .001$, $\eta_p^2 = .07$). No further comparisons were significant ($ps > .05$, $\eta_{ps}^2 < .03$). To interpret this result, the difference in flanker effect was computed as a function of the preceding cue condition. As indicated by the green arrows in Figure 3, with increasing cognitive challenge level,



	Low	Mid	High
	M (SE)	M (SE)	M (SE)
Flanker effect	144.20 (7.17)	145.83 (8.08)	126.35 (8.88)

Figure 2. Cognitive challenge effects on executive control (flanker effect). *Note.* Flanker effect is computed as RT difference [incongruent – congruent trials]. Error bars represent the standard error of the mean. Significant differences: #high vs. low: $p = .045$, $\eta_p^2 = .01$; *high vs. mid: $p = .011$, $\eta_p^2 = .02$.



	Low	Mid	High
	M (*SE*)	*M* (*SE*)	*M* (*SE*)
Double cue	149.75 (14.38)	124.68 (15.08)	89.56 (14.66)
Spatial valid cue	95.94 (8.66)	100.62 (11.41)	90.33 (9.02)

Figure 3. Cognitive challenge effects on the interactive functioning of executive control (flanker effect) and orienting (spatial attention engagement) in males.
Note. Red bars = flanker effect under double cue conditions, computed as [Double cue, flanker incongruent – Double cue, flanker congruent]. Grey bars = flanker effect under valid spatial cue conditions, computed as [Valid cue, flanker incongruent – Valid, flanker congruent]. The interactive functioning of executive control and orienting, represented by differences between red and grey bars, is computed as [(Double cue, flanker incongruent – Double cue, flanker congruent) – (Spatial valid cue, flanker incongruent – Spatial valid cue, flanker congruent)]. Error bars represent the standard error of the mean. Significant difference: #high vs. low: $p = .001$, $\eta_p^2 = .07$.

differences in flanker effect between double (red bars) and spatial valid cue conditions (grey bars) decreased. The same analyses performed on accuracy data were not significant ($ps > .05$, $\eta_p^2 < .04$).

4. Discussion

The primary aim of the present study was to investigate the dose-response relation between different levels of cognitive challenge in acute exercise and children's executive control performance using exergaming. The second aim was to test the executive control performance within the frame of the threefold attention network paradigm (Petersen & Posner, 2012) to get more insights into the efficiency of executive control along and interacting with alerting and orienting attention networks. Finally, it was also explored if the optimal dose of cognitive challenge varies according to individual characteristics. In sum, the cognitively high-challenging bout benefited children's executive control the most, whereas the efficiency of alerting and orienting networks was unaffected by the cognitive challenge level. In males only, the benefit for executive control seemed to be due to a transiently increased ability to maintain executive control efficiency also when spatial attentional resources could not be allocated in advance to support conflict resolution.

The present study is the first to directly compare, in children, the acute effects of the (individually adapted) cognitive challenge level in acute exercise on executive control, alerting, and orienting performances and interactions. Consistent with our first hypothesis, results showed that the cognitively high-challenging condition benefited children's executive control the most. In detail, children became faster in conflict resolution while maintaining a high response accuracy. This suggests a benefit for RTs without a speed-accuracy trade-off effect. According to the cognitive stimulation hypothesis,bouts of exercise performed in variable and challenging environments may activate EFs, facilitating the performance in subsequent EF tasks (Best, 2010). Combining cognitive and physical demands may produce synergistic effects due to co-activation and inter-connectedness of the neural areas associated with cognition and movement (referring broadly to the prefrontal cortex and the cerebellum, respectively; Koziol et al., 2014). A further, not mutually exclusive explanation refers to the arousal theory, as both physical exertion and cognitive engagement are arousing and thus enhance attentional resources (Lambourne & Tomporowski, 2010). An inverted U-shaped function between exercise task characteristics and cognitive functioning has been hypothesized and tested, in acute exercise research, only for exercise duration (Chang, Chu, et al., 2015) and intensity (Moreau & Chou, 2019). Regarding cognitive challenge, the current study did not confirm an inverted U-shaped function but an optimal stimulation at the highest cognitive challenge level with no performance differences at lower levels. In sum, these findings support our first hypothesis and are consistent with further studies suggesting that bouts of exercise that elicit high cognitive engagement are beneficial for children's EFs (Benzing et al., 2016; Budde et al., 2008; Flynn & Richert, 2018; Jäger et al., 2014; Schmidt et al., 2016). However, differences in quantitative and qualitative exercise task characteristics, and sample characteristics hinder a thorough comparison with previous studies. The current study used a acute 15 min bout at moderate to vigorous intensity. In previous acute cognitively challenging exercise studies with children and adolescents, durations and intensities varied largely, ranging from 10 to 50 min and from 40 to 75% HR_{max} (Schmidt et al., 2021). Detrimental effects were found only for moderate to vigorousbouts of longest durations (50 min; Gallotta et al., 2012, 2015), or of intermediate durations (20 min) but with younger children (Egger et al., 2018). As regards qualitative exercise task characteristics, most studies investigated the effect of the cognitive challenge level by comparing different exercise modalities (e.g., Bedard et al., 2021; Egger et al., 2018; van den Berg et al., 2016; Wen et al., 2021). To date, only one study manipulated the cognitive demands within the same exercise modality (exergaming; Benzing et al., 2016). The authors showed that the high-challenging condition benefitted adolescents' EFs the most, however, the cognitive demands of the acute exercise were not adjusted individually. Our study overcame this limitation by individualizing the cognitive demands (external load) through adaptation to the ongoing individual performance to limit interindividual variability in cognitive responsiveness (internal load). Thus, while corroborating Benzing et al.'s (2016) findings, the present results can be more univocally attributed to the cognitive challenge level.

Despite of the fine-graded manipulation of the exergaming task demands to generate three cognitive challenge levels (exponentially ascending number of distracting stimuli and misleading cues), the objective increase in cognitive challenge was not reflected in the subjective ratings. Children were able to discriminate only the high-challenging condition from the others, which were perceived as similarly demanding, likely because of the exponential and not linear increase in cognitive challenge across conditions. A further mismatch between objective and subjective data emerged from HR data and physical exertion ratings. Children perceived the cognitively high-challenging condition as physically more demanding, compared to the mid one, although the physical challenge (intensity, duration) was held constant, as also reflected in similar HR across conditions. Taken together, the question arises if children can clearly distinguish physical exertion and cognitive engagement inherent in acute exercise.

Regarding the second aim of the study, results showed that the cognitive challenge level in acute exercise did not influence children's alerting, orienting, or their interaction with executive control. To our knowledge, no previous studies in 'exercise and cognition' research considered the interaction between attention networks. Concerning alerting and orienting, our findings are in line with the available evidence that neither an acute demanding and varied spinning task (Chang, Pesce, et al., 2015), nor routine aerobic exercise (van den Berg et al., 2018) seems to have an effect on alerting and orienting networks. Speculatively, the fact that only executive control but no other attention networks were susceptible to acute exercise might be interpreted according to evidence showing selectively larger effects in performance for tasks that require greater inhibitory control (e.g., flanker task performance for incongruent trials; Lubans et al., 2022).

The third aim of the study was to explore the moderating role of individual characteristics. We found a sex difference in the way the acute high-challenging exercise influenced the interactive functioning of executive control (flanker effect) and orienting (spatial attention engagement). The usual effect reported in general ANT research is worse executive control when spatial attention resources cannot be validly allocated in advance (Fan et al., 2009). In our male subsample, the disadvantage in executive control, when not supported by spatial attentional allocation, was found after the low-challenging exercise condition but progressively decreased and disappeared after the high-challenging bout. These sex differences are consistent with an adult study without physical exercise (Li et al., 2021), showing that the interactive functioning of executive control and orienting networks was more efficient in males, who were less influenced by the validity of the cue. These sex differences were explained as differences in the functional interplay between separate brain areas supporting different aspects of attention. In the present study, males may have exploited the cognitive engagement generated by an acute cognitively high-challenging exercise to compensate the absence of information from external cues to maintain executive control efficiency.

Apart from sex differences, the current study found no further moderating effects of individual characteristics such as age, socio-economic, weight, pubertal status, fitness level, or need for cognition on attention network performances. It is important to consider that the qualitative and quantitative exercise task characteristics may act, individually or jointly with personal characteristics, as moderators of the acute exercise-cognition relation (Lubans et al., 2022; Pesce, 2009). The fact that no further differential effects have been found could be due to the reciprocal buffering effects of individual and task characteristics (where the latter was individualized in the current study). In the literature, there is diverging evidence on the moderating role of weight status, fitness, and academic achievement. Hwang, Hillman, Lee, Fernandez, and Lu (2021) found that obese children benefited more from cognitively challenging exergaming than their normal-weight counterparts and suggested that this may depend on their lower EFs at baseline. In contrast, Jäger et al. (2015) found that children with higher aerobic fitness and academic achievement benefited most than co-aged lower fit and lower school performers. On the one hand, children with poor baseline performance might benefit most because there is more room for improvement (Diamond & Ling, 2016; Otero, Barker, & Naglieri, 2014). Conversely, cognitively challenging bouts of exercise might benefit only children who are physically and cognitively better equipped to capitalize on it (Herold, Hamacher, Schega, & Müller, 2018, 2021).

4.1. Limitations

This study is not without limitations. First, the comparison of three cognitive challenge levels in acute exercise with counterbalanced order of experimental conditions, but without a sedentary control group, allowed identifying the optimal level of cognitive challenge in exercise but hindered disentangling physical exercise and cognitive engagement related effects. Future studies should include a sedentary control group and utilize a within-subjects crossover design. In this design, all participants engage in both the exercise and sedentary control conditions in a counterbalanced order, and individual differences and learning/practice effects can be controlled (Pontifex et al., 2019).

Second, exercise demands were specifically designed to mirror the ANT paradigm and, thus, might have primed attention effects (Moriarty et al., 2019). The available neural evidence indicates that several distinct neural mechanisms are involved in priming of attention and that priming occurs at multiple stages of perceptual processing (Brinkhuis, Kristjànsson, Harvey, & Brascamp, 2020; Kristjànsson & Àsgeirsson, 2019). These underlying mechanisms resemble those of the cognitive stimulation hypothesis, according to which the exergaming demands of the current study were specifically designed. However, differences between the computerized, sitting ANT task and the whole-body engagement in the exergame which requires gross-motor control (Koziol et al., 2014), as well as typically shorter priming duration effects (Kruijne & Meeter, 2015) render an interpretation in terms of overall priming effect less likely. It remains unclear if, besides near transfer effects of the motor and cognitive demands of the exergaming on ANT performances, far transfer effects on other EFs can also be elicited (Taatgen, 2013). Future studies should evaluate positive and negative attentional priming effects on a variety of more and less distant cognitive measures.

Third, the cognitive challenge level of the exergaming was exponentially increased from the low-to the high-challenging condition. Considering that the cognitive challenge level was individualized and continuously adapted to the performance within the predetermined difficulty levels, an exponential increase was chosen to ensure that children train around their maximum difficulty level in the high condition. To investigate differences between the low and mid conditions in further detail, future studies should explore the impact of a linear incremental trend on children's perceived cognitive engagement and EFs. Additionally, future research might (a) investigate children's ability to perceive different challenge types and the threshold needed to discriminate them, (b) validate existing subjective cognitive engagement measures, and (c) further investigate objective assessments of cognitive challenge such as brain activity or HR variability.

4.2. Conclusions

The current study extends existing evidence by manipulating the cognitive challenge level in acute bouts of exercise in an individualized manner, adapting the cognitive demands to the ongoing individual performance. An acute, cognitively high-challenging exercise transiently enhanced children's executive control but not alerting and orienting performances and interactions. For males only, this enhancement was interpretable as a more efficient executive control, also when spatial attention resources could not be validly allocated in advance. Thus, results underline the relevance of the cognitive challenge "dose" in acute exercise to increase EFs benefits in children. Further studies should investigate the dose-response relation of different durations of acute cognitively challenging exercise in depth, while controlling for the moderating role of individual characteristics. Results of this line of research may be used to implement active breaks and/or physically active learning interventions in the school setting.

Funding

This study was funded by the Swiss National Science Foundation (grant number: 181074).

Author contributions

Conception or design of the work: MS, SA, VB, AN; acquisition of data: SA; data analysis: SA, VB, CZ; interpretation of data for the work: MS, VB, SA; draft of the work: SA, VB. All co-authors revised the work critically for important intellectual content and approved the final version of the manuscript. Furthermore, all co-authors are accountable for all aspects of the work ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved.

Ethical approval

This study was conducted in the canton of Bern, Switzerland, between February 2020 and June 2022. Ethical approval was granted by the respective cantonal ethics committees (BASEC 2020-00624) and the trial was registered at ClinicalTrials.gov (DRKS00023254).

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgements

We would like to thank the participating teachers, parents and children, as well as the students who helped collecting data, and Amie Wallman-Jones for language editing.

Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.psychsport.2023.102404.

References

Appel, M., Gnambs, T., & Maio, G. R. (2012). A short measure of the need for affect. *Journal of Personality Assessment, 94*(4), 418–426. https://doi.org/10.1080/00223891.2012.666921
Bedard, C., Bremer, E., Graham, J. D., Chirico, D., & Cairney, J. (2021). Examining the effects of acute cognitively engaging physical activity on cognition in children. *Frontiers in Psychology, 12*, Article 653133. https://doi.org/10.3389/fpsyg.2021.653133
Benzing, V., Heinks, T., Eggenberger, N., & Schmidt, M. (2016). Acute cognitively engaging exergame-based physical activity enhances executive functions in adolescents. *PLoS One, 11*(12), Article e0167501. https://doi.org/10.1371/journal.pone.0167501
Benzing, V., & Schmidt, M. (2018). Exergaming for children and adolescents: Strengths, weaknesses, opportunities and threats. *Journal of Clinical Medicine, 7*(11). https://doi.org/10.3390/jcm7110422
van den Berg, V., Saliasi, E., de Groot, R. H. M., Jolles, J., Chinapaw, M. J. M., & Singh, A. S. (2016). Physical activity in the school setting: Cognitive performance is not affected by three different types of acute exercise. *Frontiers in Psychology, 7*, 723. https://doi.org/10.3389/fpsyg.2016.00723
van den Berg, V., Saliasi, E., Jolles, J., de Groot, R. H. M., Chinapaw, M. J. M., & Singh, A. S. (2018). Exercise of varying durations: No acute effects on cognitive performance in adolescents. *Frontiers in Neuroscience, 12*, 672. https://doi.org/10.3389/fnins.2018.00672
Best, J. R. (2010). Effects of physical activity on children's executive function: Contributions of experimental research on aerobic exercise. *Developmental Review, 30*(4), 331–351. https://doi.org/10.1016/j.dr.2010.08.001
Best, J. R. (2012). Exergaming immediately enhances children's executive function. *Developmental Psychology, 48*(5), 1501–1510. https://doi.org/10.1037/a0026648
Borg, G. A. (1982). Psychophysical bases of perceived exertion. *Medicine & Science in Sports & Exercise, 14*(5), 377–381.
Bradley, M. M., & Lang, P. J. (1994). Measuring emotion: The self-assessment manikin and the semantic differential. *Journal of Behavior Therapy and Experimental Psychiatry, 25*(1), 49–59. https://doi.org/10.1016/0005-7916(94)90063-9
Brinkhuis, M. A. B., Kristjànsson, A., Harvey, B. M., & Brascamp, J. W. (2020). Temporal characteristics of priming of attention shifts are mirrored by bold response patterns in the frontoparietal attention network. *Cerebral Cortex, 30*, 2267–2280. https://doi.org/10.1093/cercor/bhz238
Budde, H., Voelcker-Rehage, C., Pietraßyk-Kendziorra, S., Ribeiro, P., & Tidow, G. (2008). Acute coordinative exercise improves attentional performance in adolescents. *Neuroscience Letters, 441*(2), 219–223. https://doi.org/10.1016/j.neulet.2008.06.024
Chang, Y. K., Chu, C. H., Wang, C. C., Wang, Y. C., Song, T. F., Tsai, C. L., & Etnier, J. L. (2015). Dose-response relation between exercise duration and cognition. *Medicine & Science in Sports & Exercise, 47*(1), 159–165. https://doi.org/10.1249/MSS.0000000000000383
Chang, Y. K., Labban, J. D., Gapin, J. I., & Etnier, J. L. (2012). The effects of acute exercise on cognitive performance: A meta-analysis. *Brain Research, 1453*, 87–101. https://doi.org/10.1016/j.brainres.2012.02.068
Chang, Y. K., Pesce, C., Chiang, Y. T., Kuo, C. Y., & Fong, D. Y. (2015). Antecedent acute cycling exercise affects attention control: An ERP study using attention network test. *Frontiers in Human Neuroscience, 9*, 156. https://doi.org/10.3389/fnhum.2015.00156
Diamond, A. (2013). Executive functions. *Annual Review of Psychology, 64*, 135–168. https://doi.org/10.1146/annurev-psych-113011-143750
Diamond, A., & Ling, D. S. (2016). Conclusions about interventions, programs, and approaches for improving executive functions that appear justified and those that, despite much hype, do not. *Developmental Cognitive Neuroscience, 18*, 34–48. https://doi.org/10.1016/j.dcn.2015.11.005
Donnelly, J. E., Hillman, C. H., Castelli, D., Etnier, J. L., Lee, S., Tomporowski, P. D., Lambourne, K., & Szabo-Reed, A. N. (2016). Physical activity, fitness, cognitive function, and academic achievement in children: A systematic review. *Medicine & Science in Sports & Exercise, 48*(6), 1223–1224. https://doi.org/10.1249/MSS.0000000000000966
Egger, F., Conzelmann, A., & Schmidt, M. (2018). The effect of acute cognitively engaging physical activity breaks on children's executive functions: Too much of a good thing? *Psychology of Sport and Exercise, 36*, 178–186. https://doi.org/10.1016/j.psychsport.2018.02.014
Eriksen, B. A., & Eriksen, C. W. (1974). Effects of noise letters upon the identification of a target letter in a nonsearch task. *Perception & Psychophysics, 16*(1), 143–149.
Fan, J., Gu, X., Guise, K. G., Liu, X., Fossella, J., Wang, H., & Posner, M. I. (2009). Testing the behavioral interaction and integration of attentional networks. *Brain and Cognition, 70*(2), 209–220. https://doi.org/10.1016/j.bandc.2009.02.002
Fan, J., McCandliss, B. D., Sommer, T., Raz, A., & Posner, M. I. (2002). Testing the efficiency and independence of attentional networks. *Journal of Cognitive Neuroscience, 14*(3), 340–347. https://doi.org/10.1162/089892902317361886
Flynn, R. M., & Richert, R. A. (2018). Cognitive, not physical, engagement in video gaming influences executive functioning. *Journal of Cognition and Development, 19*(1), 1–20. https://doi.org/10.1080/15248372.2017.1419246
Gallotta, M. C., Emerenziani, G. P., Franciosi, E., Meucci, M., Guidetti, L., & Baldari, C. (2015). Acute physical activity and delayed attention in primary school students. *Scandinavian Journal of Medicine & Science in Sports, 25*(3), 331–338. https://doi.org/10.1111/sms.12310
Gallotta, M. C., Guidetti, L., Franciosi, E., Emerenziani, G. P., Bonavolontà, V., Baldari, C., & Bonavolonta, V. (2012). Effects of varying type of exertion on children's attention capacity. *Medicine & Science in Sports & Exercise, 44*(3), 550–555. https://doi.org/10.1249/MSS.0b013e3182305552
de Greeff, J. W., Bosker, R. J., Oosterlaan, J., Visscher, C., & Hartman, E. (2018). Effects of physical activity on executive functions, attention and academic performance in preadolescent children: A meta-analysis. *Journal of Science and Medicine in Sport, 21*(5), 501–507. https://doi.org/10.1016/j.jsams.2017.09.595
Herold, F., Hamacher, D., Schega, L., & Müller, N. G. (2018). Thinking while moving or moving while thinking - concepts of motor-cognitive training for cognitive performance enhancement. *Frontiers in Aging Neuroscience, 10*, 228. https://doi.org/10.3389/fnagi.2018.00228
Herold, F., Müller, P., Gronwald, T., & Müller, N. G. (2019). Dose-Response Matters! - a perspective on the exercise prescription in exercise-cognition research. *Frontiers in Psychology, 10*, 2338. https://doi.org/10.3389/fpsyg.2019.02338
Herold, F., Törpel, A., Hamacher, D., Budde, H., Zou, L., Strobach, T., Müller, N. G., & Gronwald, T. (2021). Causes and consequences of interindividual response variability: A call to apply a more rigorous research design in acute exercise-cognition studies. *Frontiers in Physiology, 12*, Article 682891. https://doi.org/10.3389/fphys.2021.682891
Hwang, J., Hillman, C. H., Lee, I. M., Fernandez, A. M., & Lu, A. S. (2021). Comparison of inhibitory control after acute bouts of exergaming between children with obesity and their normal-weight peers. *Games for Health Journal, 10*(1), 63–71. https://doi.org/10.1089/g4h.2020.0018
Jäger, K., Schmidt, M., Conzelmann, A., & Roebers, C. M. (2014). Cognitive and physiological effects of an acute physical activity intervention in elementary school children. *Frontiers in Psychology, 5*, 71. https://doi.org/10.3389/fpsyg.2014.01473
Jäger, K., Schmidt, M., Conzelmann, A., & Roebers, C. M. (2015). The effects of qualitatively different acute physical activity interventions in real-world settings on executive functions in preadolescent children. *Mental Health and Physical Activity, 9*, 1–9. https://doi.org/10.1016/j.mhpa.2015.05.002
Ketelhut, S., Röglin, L., Martin-Niedecken, A. L., Nigg, C. R., & Ketelhut, K. (2022). Integrating regular exergaming sessions in the exercube into a school setting increases physical fitness in elementary school children: A randomized controlled trial. *Journal of Clinical Medicine, 11*(6). https://doi.org/10.3390/jcm11061570
Kowalski, K. C., Crocker, P. R. E., & Faulkner, R. A. (1997). Validation of the physical activity questionnaire for older children. *Pediatric Exercise Science, 9*(2), 174–186. https://doi.org/10.1123/pes.9.2.174
Koziol, L. F., Budding, D., Andreasen, N., D'Arrigo, S., Bulgheroni, S., Imamizu, H., Ito, M., Manto, M., Marvel, C., Parker, K., Pezzulo, G., Ramnani, N., Riva, D., Schmahmann, J., Vandervert, L., & Yamazaki, T. (2014). Consensus paper: The cerebellum's role in movement and cognition. *The Cerebellum, 13*(1), 151–177. https://doi.org/10.1007/s12311-013-0511-x
Kristjànsson, A., & Àsgeirsson, A. G. (2019). Attentional priming: Recent insights and current controversies. *Current Opinion in Psychology, 29*, 71–75. https://doi.org/10.1016/j.copsyc.2018.11.013
Kruijne, W., & Meeter, M. (2015). The long and the short of priming in visual search. Attention, Perception. *Psycho, 77*, 1558–1573. https://doi.org/10.3758/s13414-015-0860-2
Lamb, K. L. (1996). Exercise regulation during cycle ergometry using the children's effort rating table (CERT) and rating of perceived exertion (RPE) scales. *Pediatric Exercise Science, 8*(4), 337–350. https://doi.org/10.1123/pes.8.4.337
Lambourne, K., & Tomporowski, P. D. (2010). The effect of exercise-induced arousal on cognitive task performance: A meta-regression analysis. *Brain Research, 1341*, 12–24. https://doi.org/10.1016/j.brainres.2010.03.091
Léger, L. A., Mercier, D., Gadoury, C., & Lambert, J. (1988). The multistage 20 meter shuttle run test for aerobic fitness. *Journal of Sports Sciences, 6*, 93–101.
Li, Y., Wang, Y., Jin, X., Niu, D., Zhang, L., Jiang, S. Y., Ruan, H. D., & Ho, G. W. (2021). Sex differences in hemispheric lateralization of attentional networks. *Psychological Research, 85*(7), 2697–2709. https://doi.org/10.1007/s00426-020-01423-z

Lubans, D. R., Leahy, A. A., Mavilidi, M. F., & Valkenborghs, S. R. (2022). Physical activity, fitness, and executive functions in youth: Effects, moderators, and mechanisms. *Current Topics in Behavioral Neurosciences, 53*, 103–130. https://doi.org/10.1007/7854_2021_271

Ludyga, S., Gerber, M., Brand, S., Holsboer-Trachsler, E., & Puhse, U. (2016). Acute effects of moderate aerobic exercise on specific aspects of executive function in different age and fitness groups: A meta-analysis. *Psychophysiology, 53*(11), 1611–1626. https://doi.org/10.1111/psyp.12736

Macleod, J. W., Lawrence, M. A., McConnell, M. M., Eskes, G. A., Klein, R. M., & Shore, D. I. (2010). Appraising the ANT: Psychometric and theoretical considerations of the attention network test. *Neuropsychology, 24*(5), 637–651. https://doi.org/10.1037/a0019803

Martin-Niedecken, A. L., Mahrer, A., Rogers, K., de Bruin, E. D., & Schättin, A. (2020). HIIT" the ExerCube: Comparing the effectiveness of functional high-intensity interval training in conventional vs. exergame-based training. *Frontiers of Computer Science, 2*. https://doi.org/10.3389/fcomp.2020.00033. Article 33.

Martin-Niedecken, A. L., Rogers, K., Turmo Vidal, L., Mekler, E. D., & Márquez Segura, E. (2019). Exercube vs. Personal trainer. In S. Brewster (Ed.), *ACM digital library, proceedings of the 2019 CHI conference on human factors in computing systems* (pp. 1–15). Association for Computing Machinery. https://doi.org/10.1145/3290605.3300318.

Moreau, D., & Chou, E. (2019). The acute effect of high-intensity exercise on executive function: A meta-analysis. *Perspectives on Psychological Science, 14*(5), 734–764. https://doi.org/10.1177/1745691619850568

Moriarty, T. A., Mermier, C., Kravitz, L., Gibson, A., Beltz, N., & Zuhl, M. (2019). Acute aerobic exercise based cognitive and motor priming: Practical applications and mechanisms. *Frontiers in Psychology, 10*, 2790. https://doi.org/10.3389/fpsyg.2019.02790

Otero, T. M., Barker, L. A., & Naglieri, J. A. (2014). Executive function treatment and intervention in schools. *Applied Neuropsychology. Child, 3*(3), 205–214. https://doi.org/10.1080/21622965.2014.897903

Paschen, L., Lehmann, T., Kehne, M., & Baumeister, J. (2019). Effects of acute physical exercise with low and high cognitive demands on executive functions in children: A systematic review. *Pediatric Exercise Science, 31*(3), 267–281. https://doi.org/10.1123/pes.2018-0215

Pesce, C. (2009). An integrated approach to the effect of acute and chronic exercise on cognition: The linked role of individual and task constraints. In T. McMorris, P. D. Tomporowski, & M. Audiffren (Eds.), *Exercise and cognitive function*. Wiley-Heinrich.

Pesce, C. (2012). Shifting the focus from quantitative to qualitative exercise characteristics in exercise and cognition research. *Journal of Sport & Exercise Psychology, 34*(6), 766–786. https://doi.org/10.1123/jsep.34.6.766

Petersen, S. E., & Posner, M. I. (2012). The attention system of the human brain: 20 years after. *Annual Review of Neuroscience, 35*, 73–89. https://doi.org/10.1146/annurev-neuro-062111-150525

Pontifex, M. B., McGowan, A. L., Chandler, M. C., Gwizdala, K. L., Parks, A. C., Fenn, K., & Kamijo, K. (2019). A primer on investigating the after effects of acute bouts of physical activity on cognition. *Psychology of Sport and Exercise, 40*, 1–22. https://doi.org/10.1016/j.psychsport.2018.08.015

Preckel, F. (2014). Assessing need for cognition in early adolescence. *European Journal of Psychological Assessment, 30*(1), 65–72. https://doi.org/10.1027/1015-5759/a000170

Schmidt, M., Benzing, V., & Kamer, M. (2016). Classroom-based physical activity breaks and children's attention: Cognitive engagement works. *Frontiers in Psychology, 7*, 1474. https://doi.org/10.3389/fpsyg.2016.01474

Schmidt, M., Egger, F., Anzeneder, S., & Benzing, V. (2021). Acute cognitively challenging physical activity to promote children's cognition. In R. Bailey (Ed.), *ICSSPE perspectives. Physical activity and sport during the first ten years of life: Multidisciplinary perspectives* (pp. 141–155). Routledge.

Taatgen, N. A. (2013). The nature and transfer of cognitive skills. *Psychological Review, 120*(3), 439–471. https://doi.org/10.1037/a0033138

Tomporowski, P. D., McCullick, B., Pendleton, D. M., & Pesce, C. (2015). Exercise and children's cognition: The role of exercise characteristics and a place for metacognition. *Journal of Sport and Health Science, 4*(1), 47–55. https://doi.org/10.1016/j.jshs.2014.09.003

Torsheim, T., Cavallo, F., Levin, K. A., Schnohr, C., Mazur, J., Niclasen, B., & Currie, C. (2016). Psychometric validation of the revised family affluence scale: A latent variable approach. *Child Indicators Research, 9*(3), 771–784. https://doi.org/10.1007/s12187-015-9339-x

Verburgh, L., Königs, M., Scherder, E. J. A., & Oosterlaan, J. (2014). Physical exercise and executive functions in preadolescent children, adolescents and young adults: A meta-analysis. *British Journal of Sports Medicine, 48*(12), 973–979. https://doi.org/10.1136/bjsports-2012-091441

Watzlawik, M. (2009). Die Erfassung des Pubertätsstatus anhand der Pubertal Development Scale. *Diagnostica, 55*(1), 55–65. https://doi.org/10.1026/0012-1924.55.1.55

Wen, X., Yang, Y., & Wang, F. (2021). Influence of acute exercise on inhibitory control and working memory of children: A comparison between soccer, resistance, and coordinative exercises. *International Journal of Sport Psychology*, (52), 101–119. https://doi.org/10.7352/IJSP.2021.52.101

Appendix A. ***Background variables***

Beside *age, biological sex* and *writing hand*, the *body weight* and *height* were measured according to standardized protocols with children wearing regular clothes without shoes. *Body Mass Index* (BMI) was calculated [weight (kg)/ height (m)^2]. *Socioeconomic status* (Torsheim et al., 2016) was assessed using the Family Affluence Scale III. This consists of six questions asking about the family (e.g., whether they have their own bedroom, number of family-owned computers). The response format varies by item and points are given for a higher number, for example of computers. The prosperity index is then calculated as the sum of the points on the six items. An acceptable reliability and validity has been demonstrated (Torsheim et al., 2016). *Pubertal developmental status* was assessed using the German version of the pubertal developmental scale (Watzlawik, 2009). This consists of three questions for each sex, asking for example: “Have you noticed a deepening of your voice?”. Responses are given on a 4-point Likert scale, scoring 1-4 points (e.g., not yet started; barely started; definitely started; seems complete). The puberty index (3-12 points) is calculated by summing up the scores of the three items. An acceptable reliability and validity has been demonstrated (Watzlawik, 2009). The *habitual physical activity* was assessed using the German version of the Physical activity questionnaire for older children (Kowalski et al., 1997). This 7-day recall instrument consists of 10 items, asking to indicate which physical activities children have performed (item 1), how physically active they were during the school hours (items 2-8), and how often they performed a moderate to vigorous activity (item 9). The response format varies by item and points are given for a higher number, for example of performed PAs. The summary score (1-5 points) is calculated by the mean of the items 1-9. Item 10 can be used to identify children who had unusual activity during the previous week. The questionnaire is a valid and reliable measure of children’s physical activity levels (Kowalski et al., 1997). The previous *videogame expertise* was assessed, asking children to indicate how long they played videogames during the last 7 days and if it was an active video game (exergaming). This questionnaire was self-developed for the purposes of the current study and has not been validated yet. *Need for cognition*, defined as disposition to engage in and enjoy effortful cognitive endeavors (Cacioppo et al., 1984), was assessed using the German teen version of the Need for Cognition scale (Preckel, 2014). This consists of 19 questions, asking for example: "I would rather do something that requires little thought than something that is sure to challenge my thinking abilities?". Responses are given on a 5-point Likert scale, scoring 1-5 points (from extremely uncharacteristic of me to extremely characteristic of me). Some items are reverse scored. The total score (19-95 points) is calculated by summing up the scores of the 19 items. An acceptable reliability and validity has been demonstrated (Preckel, 2014). *Need for affect*, which is the motivation to approach or avoid emotion-inducing situations and activities, was assessed using the German version of the Need for Affect Questionnaire (Appel et al., 2012). It consists of 10 items, asking for example "It is important for me to know how others are feeling". Responses are given on a 6-point Likert scale, scoring from -3 to +3 points (from extremely uncharacteristic of me to extremely characteristic of me). The sum of reverse scored items correspond to the avoidance subscale, whereas the sum of the positive scored items to the approach subscale. The total score (-30 to 30 points) is calculated by summing up the avoidance and the approach subscales. An acceptable reliability and validity has been demonstrated (Appel et al., 2012). *Cardiovascular fitness* (Vo^2max) and HR_{max} were assessed by a 20-m Shuttle Run test (Léger et al., 1988). All participants wore a Polar H7 HR monitor that was connected to the Polar Team App (Polar Electro Oy, Finland), in which HR data was stored. The test was performed during a regular physical education lesson, under supervision of a physical education teacher. All children were familiar with this test and were encouraged by their teacher and the research team to exert maximum performance. The test had an initial running speed of 8.0 km/h that progressively increased with 0.5 km/h in one-minute stages. The highest completed stage with an accuracy of half a stage was recorded.

Appendix B. ***Exergaming tasks***

ExerCube game setup:

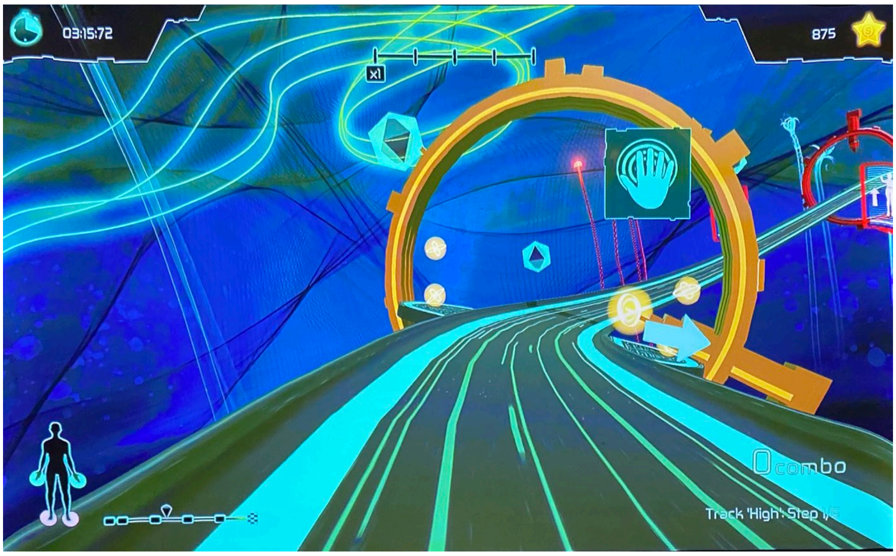
Exergaming video: **https://vimeo.com/759054046**

Exergaming elements in a catching point example:

1. First, a cue appears on the right, left or both sides of a colored gate

2. When the gate comes closer, children have to perform a lateral shuffle step and catch a yellow point (other gates can request punches, skipping, jumps, squats or deep lunges).

3. Movements must be performed following the direction of the target arrow, while ignoring the rotation (to the right or to the left) of the central distracting point (can be congruent or incongruent with the arrow direction; in the picture below the central point is congruent)



Examples of movements used to manipulate the cognitive challenge:

Picture 1. ***Punches with congruent stimuli but double (not spatial informative) cue***

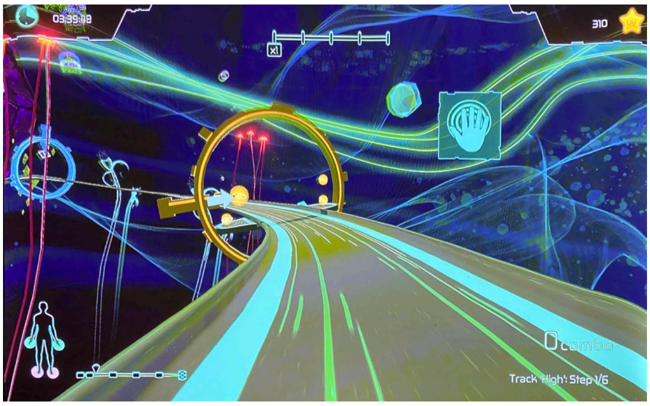
Children's task is to follow the direction of the target arrow (pointing here to the left), while ignoring the rotation of the central quadrangle (here to the left and therefore congruent). The double cue is not spatial informative (fists on both sides).

Picture 2. ***Punches) with distracting stimuli but valid cue***

Children's task is to follow the direction of the target arrow (pointing here to the left), while ignoring the rotation of the central quadrangle (here to the right and therefore incongruent). The cue is valid (fist on the left side).

Picture 3. ***Catching a sideway point with congruent stimuli but misleading cue***

Children's task is to follow the direction of the target arrow (pointing here to the right), while ignoring the rotation of the central point (here to the right and therefore congruent). The cue is misleading (hand on the left side).

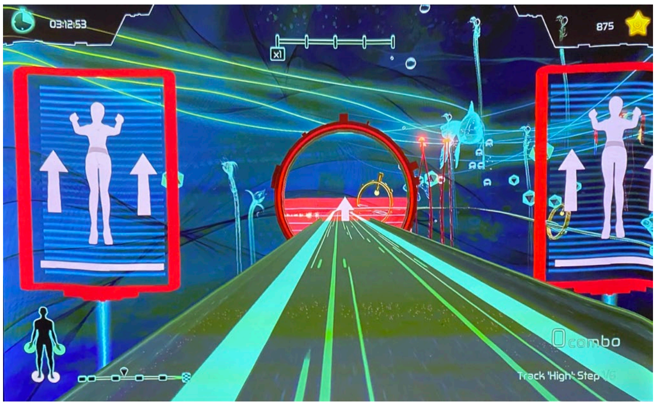


Picture 4. ***Catching a sideway point with distracting stimuli but correct cue***

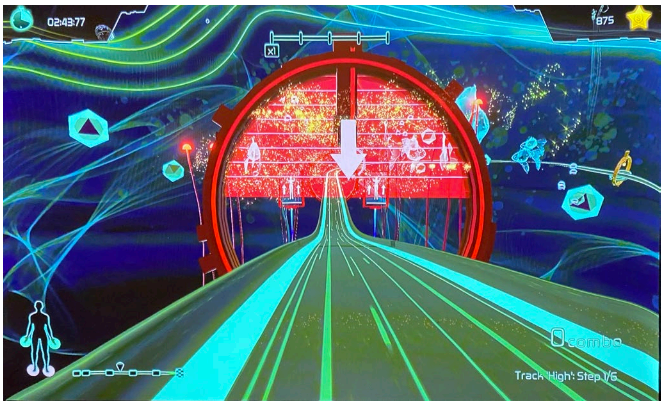
Children's task is to follow the direction of the target arrow (pointing here to the right), while ignoring the rotation of the central point (here to the left and therefore incongruent). The cue is misleading (hand on the right side).

Examples of movements used to maintain children's heart rate constant

Picture 4. *Skipping*

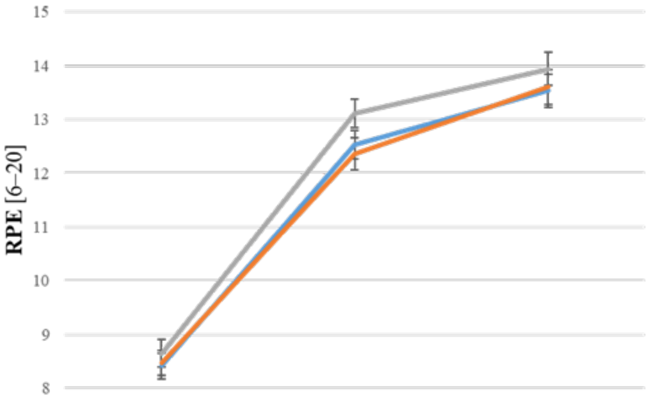


Picture 5. *Jumps*

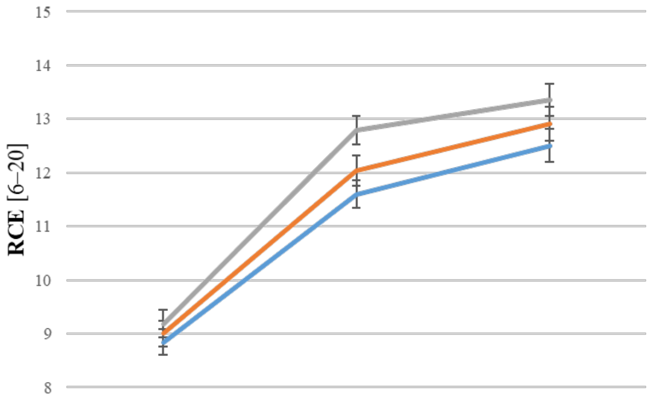


Picture 6. *Squats*

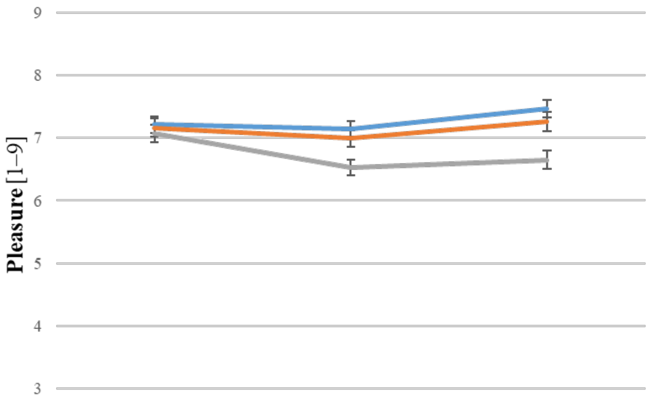
Appendix C. ***Descriptive statistics of manipulation check and control variables among cognitive challenge conditions (low, mid, high) and time points (pre, during, post; except for HR averaged across the exergaming)***



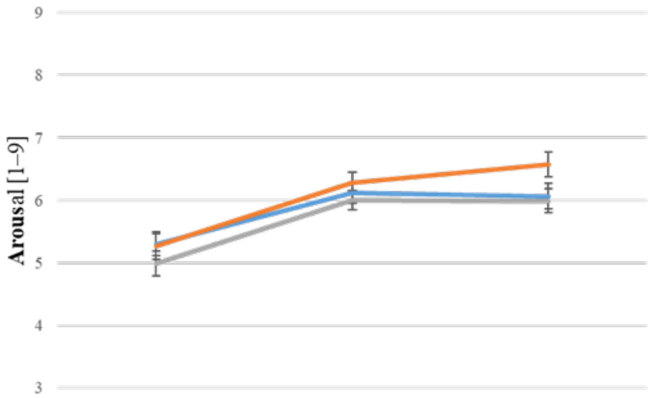
	Pre	During	Post
	M (*SE*)	*M* (*SE*)	*M* (*SE*)
Low	8.42 (0.24)	12.53 (0.27)	13.53 (0.31)
Mid	8.47 (0.23)	12.36 (0.29)	13.60 (0.32)
High	8.65 (0.26)	13.11 (0.26)	13.94 (0.30)



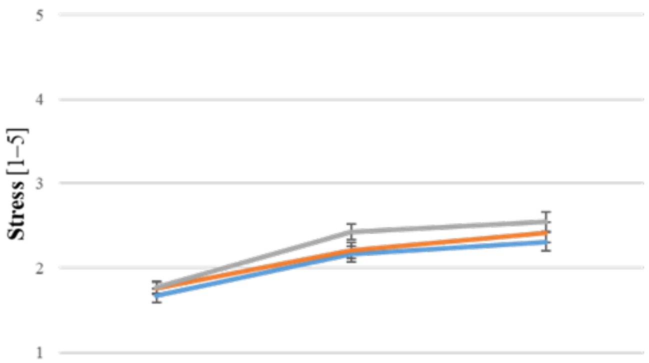
	Pre	During	Post
	M (*SE*)	*M* (*SE*)	*M* (*SE*)
Low	8.84 (0.24)	11.60 (0.26)	12.50 (0.31)
Mid	9.00 (0.23)	12.04 (0.28)	12.91 (0.32)
High	9.18 (0.26)	12.79 (0.27)	13.36 (0.30)



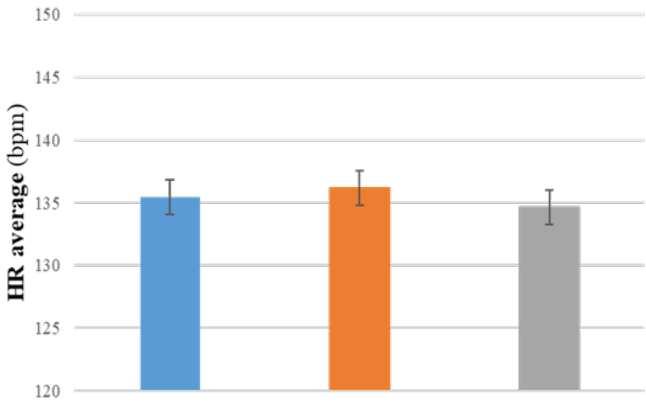
	Pre	During	Post
	M (*SE*)	*M* (*SE*)	*M* (*SE*)
Low	7.21 (0.13)	7.15 (0.13)	7.47 (0.14)
Mid	7.17 (0.14)	6.99 (0.13)	7.26 (0.15)
High	7.07 (0.14)	6.52 (0.13)	6.65 (0.15)



	Pre	During	Post
	M (*SE*)	*M* (*SE*)	*M* (*SE*)
Low	5.30 (0.19)	6.12 (0.16)	6.07 (0.20)
Mid	5.26 (0.20)	6.28 (0.17)	6.57 (0.20)
High	4.99 (0.20)	6.00 (0.16)	5.99 (0.19)



	Pre	During	Post
	M (*SE*)	*M* (*SE*)	*M* (*SE*)
Low	1.67 (0.08)	2.16 (0.09)	2.31 (0.11)
Mid	1.76 (0.07)	2.20 (0.09)	2.42 (0.12)
High	1.77 (0.07)	2.42 (0.09)	2.54 (0.11)



Low	Mid	High
M (*SE*)	*M* (*SE*)	*M* (*SE*)
135.45 (1.52)	136.18 (1.48)	134.63 (1.39)

Note. RPE: rating of perceived exertion RCE: rating of cognitive engagement. During = mean of T_1 and T_2. Error bars represent the standard error of the mean. Results of post-hoc comparisons (significant results bolted): RPE high vs. low: $p = .091$, $\eta^2_p = .02$; **RPE high vs. mid**: $p =$ **.048**, $\eta^2_p = .03$; RPE mid vs. low: $p = 1.00$, $\eta^2_p = .00$. **RCE high vs. low**: $p <$ **.001**, $\eta^2_p = .07$. **RCE high vs. mid**: $p =$ **.045**, $\eta^2_p = .03$. RCE mid vs. low: $p = .256$, $\eta^2_p = .02$. **Pleasure high vs. low**: $p <$ **.001**, $\eta^2_p = .04$; **Pleasure high vs. mid**: $p =$ **.006**, $\eta^2_p = .02$; Pleasure mid vs. low: $p = .540$, $\eta^2_p = .01$. Arousal high vs. low: $p = .780$, $\eta^2_p = .03$; **Arousal high vs. mid**: $p =$ **.031**, $\eta^2_p = .02$; Arousal mid vs. low: $p = .520$, $\eta^2_p = .03$. **Stress high vs. low**: $p =$ **.009**, $\eta^2_p = .02$; Stress high vs. mid: $p = .200$; $\eta^2_p = .02$; Stress mid vs. low: $p = .776$, $\eta^2_p = .02$.

Supplementary material

II

Anzeneder, **S.**, Zehnder, C., Schmid, J., Martin-Niedecken, A. L., Schmidt, M., & Benzing, V. (2023b). Dose-response relation between the duration of a cognitively challenging bout of physical exercise and children's cognition. *Scandinavian Journal of Medicine & Science in Sports*, *33*(8), 1439-51. https://doi.org/10.1111/sms.14370

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Received: 23 December 2022 | Revised: 8 March 2023 | Accepted: 31 March 2023
DOI: 10.1111/sms.14370

ORIGINAL ARTICLE

WILEY

Dose–response relation between the duration of a cognitively challenging bout of physical exercise and children's cognition

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Funding information
Swiss National Science Foundation, Grant/Award Number: 181074

Abstract
Acute bouts of physical exercise have the potential to benefit children's cognition. Inconsistent evidence calls for systematic investigations of dose–response relations between quantitative (intensity and duration) and qualitative (modality) exercise characteristics. Thus, in this study the optimal duration of an acute cognitively challenging physical exercise to benefit children's cognition was investigated, also exploring the moderating role of individual characteristics. In a within-subject experimental design, 104 children (M_{age} = 11.5, SD = 0.8, 51% female) participated weekly in one of four exergaming conditions of different durations (5, 10, 15, 20 min) followed by an Attention Network task (ANT-R). Exergame sessions were designed to keep physical intensity constant (65% HR_{max}) and to have a high cognitive challenge level (adapted to the individual ongoing performance). Repeated measures ANOVAs revealed a significant effect of exercise duration on reaction times (RTs; p = 0.009, η^2_p = 0.11), but not on response accuracy. Post hoc analyses showed faster information processing speed after 15 min of exercise compared to 10 min (p = 0.019, η^2_p = 0.09). Executive control, alerting and orienting performances and interactions were unaffected by exercise duration (p_s > 0.05). Among individual characteristics, habitual physical activity moderated duration effects on RTs. For more active children, exercise duration influenced the interaction between executive control and orienting (p = 0.034; η^2_p = 0.17) with best performances after the 15 min duration. Results suggest that an acute 15 min cognitively high-challenging bout of physical exercise enhances allocable resources, which in turn facilitate information processing, and—for more active children only—also executive processes. Results are interpreted according to the arousal theory and cognitive stimulation hypothesis.

Mirko Schmidt and Valentin Benzing share senior authorship.

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KEYWORDS
acute physical activity, Attention Network task, cognitive engagement, executive function, exergaming, inhibition

1 | INTRODUCTION

Acute physical exercise (i.e., a single bout of exercise) has the potential to transiently enhance subsequent cognitive performance,[2,3] especially in children.[4] Cognitive benefits of acute physical exercise are largely influenced by the interaction of quantitative (duration, intensity) and qualitative exercise characteristics (modality),[5,6] as well as by the responsiveness of individuals with different characteristics (e.g., environmental, developmental, physical, and cognitive).[1,7] Chronic cognitively challenging physical exercise, which elicits cognitive engagement,[†] appears to have positive effects on children's cognition.[9] Concerning immediate after-effects of an acute cognitively challenging physical exercise, however, results are inconsistent.[10,11] It is still unclear which duration of cognitively challenging bouts of physical exercise benefits cognition the most. This is of great practical importance in the educational setting for designing active breaks to enhance cognitive functions essential for learning and academic achievement, such as attention and executive functions (EFs). While attention encompasses different processes related to how the organisms becomes receptive to internal and external stimuli and how it begins to process them,[12] EFs refer to higher-level functions that enable self-regulation and goal-directed behavior.[13]

A function at the intersection between the broad and multifaceted constructs of attention and EFs is executive control, that is, the ability to exert control over interference. Executive control is a component of inhibition, along with response inhibition (suppressing or resisting automatic responses) and cognitive inhibition (suppressing thoughts and memories).[13] It is one of three independent yet interacting attention networks, along with alerting (achieving and maintaining an alert state) and orienting (selecting information from sensory input).[14,15]

Meta-analyses revealed that acute physical exercise has positive effects on children's executive control with ES ranging from 0.28 to 0.57.[16,17] Although these positive results seem relatively consistent, there is considerable heterogeneity in the magnitude of effects.[5] Therefore, research increasingly focused on dose–response relationships between exercise characteristics, cognitive outcomes, and underlying mechanisms. The dose–response relation in children and adolescents has been mostly investigated by manipulating exercise intensity and less frequent exercise duration.[2,5,18] Correspondingly, while meta-analytic findings suggest that bouts of physical exercise with at least moderate intensity are most beneficial for EFs (when cognitive performance is assessed following a delay of more than 1 min)[2,5] with no differences between moderate and vigorous intensities,[18] they do not allow to univocally identify an optimal exercise duration.[16,17] Furthermore, the few child and adolescent studies that have manipulated the duration of acute bouts of physical exercise are hardly comparable due to differences in both exercise intensity and modality.[19–22] Differences in modality, such as in cognitive challenge and related cognitive engagement, are thought to contribute to exercise effects on cognitive performance.[6]

Therefore, increasing research investigated qualitative exercise characteristics such as the cognitive challenge level.[10,11] However, no acute cognitively challenging exercise studies manipulated bout duration. In children and adolescents, acute cognitively challenging exercise studies showed a mixed pattern of results.[10,11] In the duration range most frequently used (10–20 min), acute cognitively challenging bouts of physical exercise at moderate to vigorous intensity resulted in facilitation,[23–27] no effects,[28–31] or even detrimental effects on cognition.[32] Conversely, longer exercise durations (40 and 50 min) elicited either no effects or detrimental effects, respectively.[33–35] A univocal synthesis of the above studies is limited by the variety of modalities used. To identify optimal exercise characteristics for children's cognition, further research that systematically investigates the effects of acute cognitively challenging exercise of different durations on attention and EFs, holding modality constant, is needed.

Moreover, the pattern of moderators acting on the acute exercise-cognition relation is complexified by the individual responsiveness to physical and cognitive challenges of bouts of physical exercise.[1,7] Previous evidence recommends to finely tune exercise demands to children's developmental level and expertise[36] as well as to their physical and cognitive abilities.[4,7,37] Depending on these abilities, the combination of acute exercise's varying physical and cognitive demands may be under- or over-challenging.[11,32]

*In 'exercise and cognition' research, the meaning of the term 'exercise' has been expanded to encompass any specific form of physical activity that is planned, structured, and purposive to maintain or improve outcomes in different domains (e.g., physical, cognitive).[1]

[†]To distinguish it from behavioral and emotional engagement, cognitive engagement can be defined as the degree to which the allocation of attentional resources and cognitive effort is needed to master difficult skills.[8]

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In sum, to design acute bouts of physical exercise for children that transiently enhance cognitive function, it is essential to consider dose–response relations within the frame of quantitative and qualitative exercise characteristics, as well as the individual responsiveness to acute bouts of physical exercise.

Thus, the *first aim* of the present study was to investigate which duration of an acute cognitively challenging bout of physical exercise benefits children's executive control the most. Considering that studies investigating single durations of cognitively challenging bouts of physical exercise led to inconsistent evidence in the 10–20 min range,[11] we investigated multiple durations up to 20 min. In line with overall meta-analytic findings across the lifespan, showing that neither shorter (e.g., 5 min)[2] nor longer duration (e.g., 20 min)[38] of acute physical exercise benefits cognition, we hypothesized that intermediate durations (10 and 15 min) would elicit larger executive control gains compared to shorter and longer ones. The *second aim* was to investigate whether the duration of an acute cognitively challenging bout of physical exercise affects not only executive control, but also alerting and orienting performances, as well as their interactive functioning (i.e., the effect of alerting or orienting on executive control efficiency[14]), which in turn seem to underlie cognitive and emotional control processes relevant for academic learning.[39] However, considering that acute physical exercise studies addressing after-effects on alerting and orienting are limited and inconsistent[22,40] and none investigated the interaction among attention networks, no a priori hypothesis was stated. The *third exploratory aim* was to evaluate whether individual characteristics interact with exercise duration. Given the limited evidence on the moderating role of individual characteristics regarding the effects of acute cognitively challenging bouts of physical exercise,[11,36] no a priori hypothesis was stated, and a wide range of environmental, developmental, physical, and cognitive characteristics were included in these exploratory analyses.

2 | METHODS

This study was part of the project "School-based physical activity and children's cognitive functioning: The quest for theory-driven interventions." The project aims to investigate the effects of qualitative and quantitative characteristics of designed, school-based, bouts of physical exercise on children's cognitive functions. The project was preregistered in the German Clinical Trials Registry (registration number: DRKS00023254). The cantonal ethics committee approved the study protocol (number: 2020-00624), which adhered to the latest Declaration of Helsinki.

2.1 | Participants

One hundred four children aged 10–13 years ($M = 11.5$, $SD = 0.8$; 51% female) were recruited from three primary schools in the region of Bern, Switzerland. The legal guardians of all children provided informed written consent and children agreed to participate. Exclusion criteria were any neurological, developmental, or medical condition that would affect the subjects' integrity or study results. We conducted a power analysis using the SuperPower Shiny app (https://shiny.ieis.tue.nl/anova_power/) to determine sample size. We defined a within-subjects design with four exercise duration conditions and estimated effects based on previous studies[23,25,29] with alpha error probability = 0.05 and correlation between the repeated measures $r = 0.61$. We assumed that children's executive control performance (as difference value, see "Cognitive measures" section) would be faster after the 10 min ($M = 100$ ms, $SD = 80$) and 15 min conditions ($M = 100$ ms, $SD = 80$; with no significant differences between the 10 min and 15 min conditions), compared to the 5 min ($M = 125$ ms, $SD = 80$) and 20 min ones ($M = 125$ ms, $SD = 80$; with no significant differences between the 5 min and 20 min conditions). To satisfy counterbalancing requirements, we tested the power of $N = 100$ participants. Using 2000 simulations, results showed a power of 99% for repeated measures ANOVAs and more interestingly a power of > 80% for Bonferroni-adjusted *t*-test comparisons (6 comparisons) of above hypothesized significant differing conditions (5 vs. 10 min, 5 vs. 15 min, 10 vs. 20 min, 15 vs. 20 min).

Of the 114 participants initially recruited, four were injured during the intervention period outside the study (e.g., at home) and six were identified as multivariate outliers based on Mahalanobis distance ($p < 0.001$), and were therefore excluded. Due to technical problems with the tablets used for attentional testing (SurfTab 10.1; TrekStor GmgH), there was some loss of data (3.1%). Since Little's MCAR test has led to a non-significant result ($p = 0.986$), the missing values were imputed using the expectation–maximization algorithm. Participants' background variables are presented in Table 1.

2.2 | Design and procedures

In the current within-subjects crossover design study with counterbalanced order of experimental conditions (24 possible permutations), the duration of an acute cognitively challenging, exergame-based, bout of physical exercise was manipulated to be 5, 10, 15, or 20 min (C5, C10, C15, C20).

The study was conducted over a period of 5 weeks. During the first study week, data were collected on two

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separate days. On the first day, background characteristics were assessed by a questionnaire, including age, biological sex, height, weight, socioeconomic status, pubertal developmental status, habitual physical activity, need for cognition, and weekly videogame practice. Subsequently, children performed a 20-m Shuttle Run test to assess their maximum heart rate (HR) and fitness level. Acceptable reliability and validity were demonstrated for background variables; only the videogame practice questionnaire was self-developed for the purposes of the current study (for a detailed description and references of background variables see Appendix S1). At the second visit, children participated in a familiarization session. Each child completed a specifically developed tutorial of the exergame. Gameplay (each movement) was explained and the exergame continued only when movements were carried out correctly. After the tutorial, children participated in a 3 min regular version of the exergame. Subsequently, to familiarize children with attentional testing, they performed the practice block of the cognitive tests (for details, see "Cognitive measures").

TABLE 1 Participant's background variables.

Background variables	*M* (*SD*)
Age (years)	11.5 (0.8)
Biological sex (% female)	51%
Socioeconomic status [2–14]	8.4 (2.1)
Body mass index (kg/m^2)	18.7 (3.3)
Pubertal developmental status [3–12]	5.8 (2.2)
Habitual physical activity [1–5]	2.6 (0.5)
VO_{2max} (mL/kg/min)	51.5 (6.8)
Weekly videogame practice (min)	194.7 (237.4)
Need for cognition [19–95]	62.2 (12.6)

Children played one exergaming session per week between the second and fifth week. Before, during, and after the exergame, manipulation check and control variables were collected. These measures have acceptable reliability and validity (for a detailed description and references see Appendix S1). During the exergaming task, HR was continously monitored. Each session included a short assessment before exergaming, 2 min warm-up, 5–20 min of exergaming (depending on condition) intermitted by short assessment breaks every 5 min, a short assessment immediately after exergaming, a water break, and the

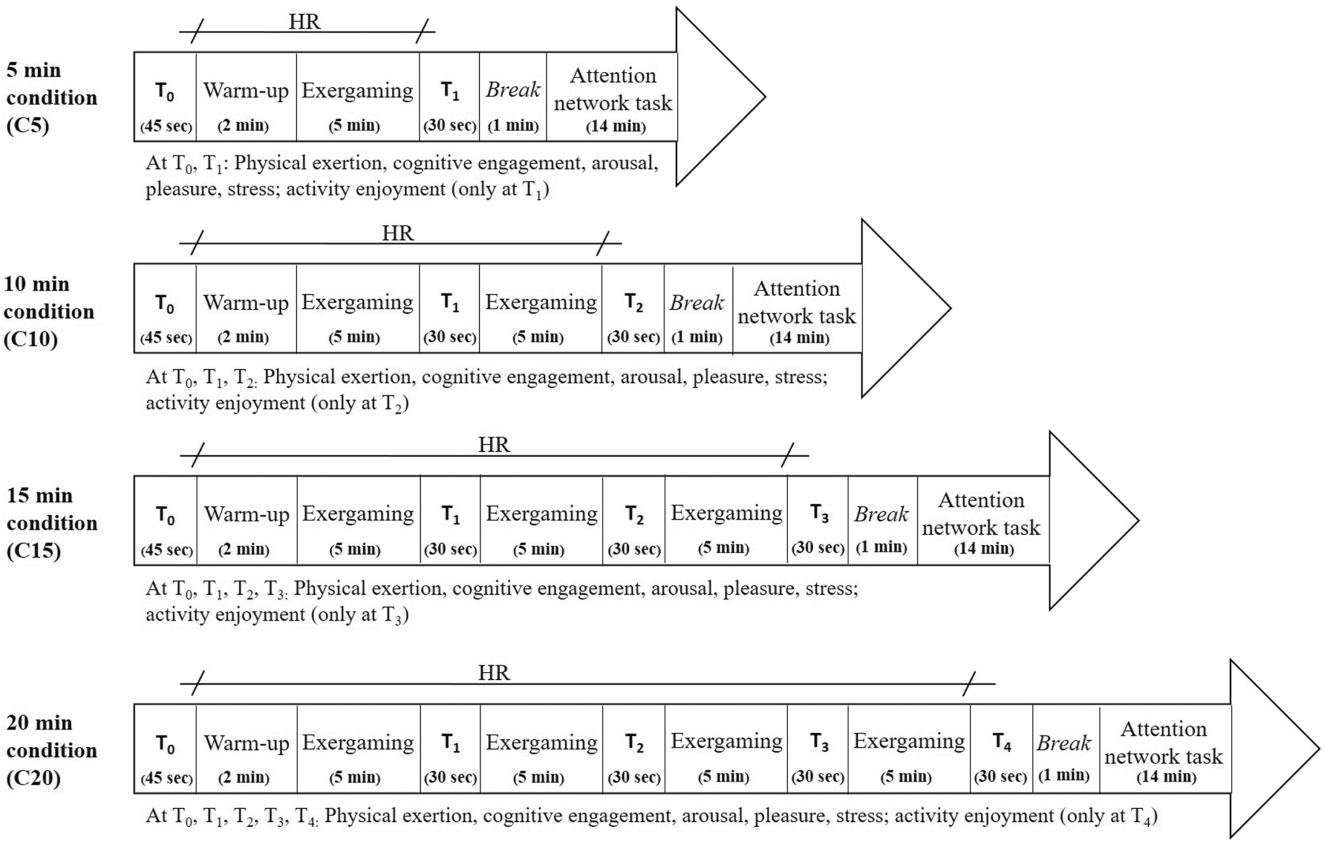

FIGURE 1 Experimental protocol of the weekly sessions (which were carried out in a counterbalanced order). *Note*: T = assessment times; T_0 = before activity (pre); T_1 = after 5 min activity; T_2 = after 10 min activity; T_3 = after 15 min activity; T_4 = after 20 min activity; HR = heart rate.

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subsequent attentional testing with the revised Attention Network task (ANT-R).[14] In total, C5, C10, C15, and C20 sessions lasted about 23 min, 29 min, 34 min, and 40 min, respectively. The experimental protocol and timeline of the respective weekly session are depicted in Figure 1. While children were blinded to the conditions, assessors were not, since they had to stop the exergaming after 5, 10, 15, and 20 min, respectively. However, the ANT-R is a highly standardized tablet-based test.[14] Thus, assessors most probably did not bias the cognitive outcome measure.

2.3 | Intervention and experimental conditions

We used an exergame in the school setting to manipulate and individualize both physical and cognitive exercise challenges in a highly controlled and ecologically valid fashion. Exergaming refers to active video gaming that embeds gross-motor exercise into videogame play.[41] The exergame sessions took place during school hours and were performed individually, once weekly, at the same time and day each week. The intervention consisted of a modified version of the exergame Sphery Racer.[42] To control the exergame, participants performed different functional workout movements (e.g., jumps, squats, or punches) while being immersed in a rapid underwater race game scenario. In this game scenario, they navigated an avatar and passed various colored gates, which provided them with information regarding respective functional workout movements and cognitive tasks to be performed. During the exergame session, participants wore four motion-based trackers (HTC Vive tracking sensors, Vive) attached to their wrists and ankles as well as an HR sensor (Polar Team2 straps and transmitters; Polar Electro) to constantly track their movements and body position, and their HR, respectively. The physical intensity was held constant during the session at approximately 65% HR_{max}. Most of the previous research in this area investigated moderate to vigorous intensities,[3] showing beneficial effects.[4,43,44] Therefore, a similar intensity was chosen for comparability reasons and to avoid overload because of the potential combined effects of physical intensity and cognitive challenge. The cognitive challenge level of the exergame was chosen according to the results of a previous study,[45] showing that a high-challenging bout enhanced children's executive control more than less challenging versions of the same exergame. Jumps, squats, skipping, and deep lunges were used to maintain HR constant (50% of total movements) while punches and catching sideway points were used to manipulate the cognitive challenge (50% of total movements). The latter, more cognitively challenging movements, were designed to mirror attentional allocation processes involved in the ANT-R paradigm (see "Cognitive measures" section). The tasks included anticipatory cues that alerted and oriented attention and targets that required movement actions while ignoring distracting stimuli (for details on exergaming tasks see description and video in Appendix S2). During the exergame session, the level of cognitive challenge was constantly adapted to the individual ongoing performance. The task was rendered easier or more difficult if the participant made more or less than three errors in a period of 30 seconds, respectively. Task difficulty was modulated by an ascending number of distracting stimuli (40%–60%) and misleading cues (13%–19%), which preceded punches and lateral shuffle steps (i.e., catching sideway points).

2.4 | Manipulation check

Several variables were assessed to test whether experimental manipulation had succeeded (see Figure 1). PolarTeam2 belts and transmitters were used to measure *children's HR* during exergaming (measurement every 3 seconds) and to adjust the physical intensity at 65% HR_{max}. In addition, *perceived physical exertion* (RPE) and *cognitive engagement* (RCE) were measured using the Borg RPE and the adapted RCE scales (for a detailed description and references see Appendix S1).

2.5 | Control variables

According to previous evidence highlighting that affective states elicited by acute exercise need to be considered,[27,28] several control variables were assessed (see Figure 1). *Arousal*, *pleasure*, and *perceived stress* were assessed using the single-item pictorial Self-Assessment-Manikin, and *enjoyment* with the physical activity enjoyment scale (for a detailed description and references see Appendix S1).

2.6 | Cognitive measures

A child-adapted version of the ANT-R[14] was used on Inquisit 5 (Millisecond Software) to assess the efficiency of (a) *executive control* (primary outcome), (b) *alerting* and *orienting networks*, and (c) the *influence of alerting and orienting networks on executive control*. For the primary outcome, a retest reliability ranging from 0.61 to 0.71 has been shown.[46]

To capture the functioning of attention network systems, the test combines the Attention cueing paradigm that assesses alerting and orienting, and the Flanker task

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that assesses executive control. There are four cue conditions: no cue, double cue, valid spatial cue, and invalid spatial cue; and two congruency conditions: a central target arrow surrounded by congruent (>>>>> or <<<<<) or incongruent (>><>> or <<><<) lateral flanker arrows. Each trial begins with a central fixation cross, followed by no cue, a double cue informing that a target will occur soon, or a single spatial cue informing on the probable location of the upcoming target. A valid spatial cue indicates the location in which a subsequent target most probably will appear. An invalid spatial cue indicates the opposite location. Subsequently, a congruent or incongruent flanker condition appears. The child's task is to identify the direction of the center arrow by pressing a right or left button, while ignoring lateral flanker arrows. Reaction times (RTs) and response accuracy are recorded. The task is composed of two blocks of 72 trials (each bock with 12 no cue, 12 double cue, 36 valid spatial and 12 invalid spatial trials) and lasts 14 min, including a one-min break between blocks. Responses with RTs faster than 200 ms or longer than 1700 ms were excluded automatically.[14] Further details on the task parameters and cue-target interval timing can be found elsewhere.[14] Each attention system performance is computed as a difference value of RTs and accuracy.

- *Executive control* (flanker effect) is calculated as (incongruent – congruent trials). A smaller value for the RT difference and a smaller negative value for the accuracy difference reflect a better efficiency, because children are better able to inhibit the interference of incongruent flankers.
- *Alerting* is calculated as (no cue – double cue trials). A larger value for the RT difference and a larger negative value for the accuracy difference reflect the benefit in speed/accuracy elicited by an alerting cue.
- *Orienting* is composed of *engaging* attention at a validly cued location (double cue – valid spatial cue trials) and *disengaging* attention from an invalidly cued location (invalid spatial cue – double cue trials). A larger RT difference and a larger negative value for the accuracy difference reflect the benefit in speed/accuracy elicited by a valid spatial cue, and/or the cost elicited by an invalid spatial cue.

The interactive function of attention networks is assessed as the effect of alerting or orienting on executive control (flanker effect). It is measured as the difference of flanker effect under different cue conditions.

- The *effect of alerting on executive control* is calculated as ([no cue trials with incongruent flanker – no cue trials with congruent flanker] – [double cue trials with incongruent flanker – double cue trials with congruent flanker]). A negative value indicates a negative impact of alerting on executive control.
- The *effect of orienting on executive control* is composed of the effects of *engaging* and *disengaging* attention on executive control. The effect of *engaging* is calculated as ([double cue trials with incongruent flanker – double cue trials with congruent flanker] – [valid spatial cue trials with incongruent flanker – valid spatial cue trials with congruent flanker]). The effect of *disengaging* is calculated as ([invalid spatial cue trials with incongruent flanker – invalid spatial cue trials with congruent flanker] – [double cue trials with incongruent flanker – double cue trials with congruent flanker]). For *engaging*, a positive value indicates the beneficial effect of a validly oriented attention on executive control. Instead, for *disengaging*, a positive value indicates the cost of an invalidly oriented attention.

2.7 | Statistical analyses

All analyses were performed using SPSS version 27.0 (SPSS Inc.). Preliminary analyses were run using repeated measures ANOVAs for the comparison of manipulation check (RPE, RCE) and control variables (arousal, pleasure, stress) among exergaming time (Pre, During, and Post; see Figure 1) separately for each duration condition (C5, C10, C15, C20). Subsequent ANOVAs were run for the comparison of manipulation check and control variables among conditions at Pre to test for baseline differences. If baseline differences emerged, ANOVAs to test for the effect of duration were performed using (Post – Pre) delta scores in absolute value. Analyses were performed as well on delta scores in relative value ([Post – Pre]/Pre and [Post – Pre]/[Post + Pre]) and results depicted scores in absolute value. Further ANOVAs were run for the comparison among duration conditions (C5, C10, C15, C20) of (a) HR average during exergaming and (b) activity enjoyment after exergaming. Post hoc Bonferroni-adjusted pairwise comparisons for the effect of duration are reported.

To analyze the effect of duration on overall RTs and response accuracy as a function of attentional factors (cue and flanker conditions that depict attention network performances), a 4 (duration conditions) × 4 (cue conditions) × 2 (flanker conditions) repeated measures ANOVAs were performed, separately for RTs and response accuracy. Post-hoc Bonferroni-adjusted pairwise comparisons were reported for the effect of duration.

To explore the moderating role of individual characteristics (age, sex, socioeconomic status, BMI, pubertal status, habitual physical activity, VO_2max, videogame practice, need

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for cognition) on the effect of exercise duration on attention networks, continuous individual background variables were first dichotomized (i.e., median split). Subsequently, they were included as categorical moderators in ANOVAs on RT and accuracy difference values reflecting attention network performances and interactions (RT and accuracy under the different cue and flanker conditions were reduced in a theory-based manner; see "Cognitive measures" section). In the case of significant interactions including potential moderators, performances after the four duration conditions were contrasted by means of post-hoc ANOVAs, separately for each group of children (e.g., low and high habitual physical activity), and subsequent Bonferroni-adjusted pairwise comparisons.

For all analyses, median RTs were used because of the disproportional contribution of outliers in mean RTs for different participants and due to the non-normal distribution of RTs. All analyses were performed also on mean RTs, with and without the six multivariate outliers. Results depict median RTs with multivariate outliers excluded. The level of significance was set at $p<0.05$ for all analyses, and η^2_p was reported as an estimation of effect size (small effect size = 0.01, medium effect size = 0.06, large effect size = 0.14).

3 | RESULTS

3.1 | Manipulation check

Statistics of manipulation check variables among duration conditions (C5, C10, C15, C20) and time points (Pre, During, Post) are presented in Appendix S3. First ANOVAs, performed separately for each duration condition (C5, C10, C15, C20), revealed in all conditions a significant effect of time on RPE ($p_s < 0.001$; $\eta^2_{ps} > 0.63$) and RCE ($p_s < 0.001$; $\eta^2_{ps} > 0.41$). Further ANOVAs on delta scores (Post − Pre) among duration conditions revealed a significant effect of duration for RPE (duration: F (3, 101) = 5.16, $p=0.002$, $\eta^2_p=0.13$) and RCE (duration: F (3, 101) = 6.02, $p=0.001$, $\eta^2_p=0.15$). As concerns the effect of duration, Bonferroni-adjusted pairwise comparisons showed that C5 was perceived as less physically exerting and cognitively engaging compared to C15 (RPE: $p=0.006$, $\eta^2_p=0.10$; RCE: $p=0.004$, $\eta^2_p=0.11$) and C20 (RPE: $p=0.003$, $\eta^2_p=0.11$; RCE: $p=0.001$, $\eta^2_p=0.13$), whereas the shortest (C5 vs. C10) and longest conditions (C15 vs. C20) were perceived as equally demanding ($p_s > 0.999$, $\eta^2_{ps} < 0.01$; see Appendix S3). The difference in RPE among conditions was not paralleled by objective HR data ($p=0.403$; $\eta^2_p=0.03$), which was designed to be similar across conditions.

3.2 | Control variables

Statistical analyses of control variables among duration conditions (C5, C10, C15, C20) and time points (T_0, T_1, T_2, T_3, T_4) are presented in Appendix S3. First ANOVAs, performed separately for each duration condition (C5, C10, C15, C20), showed in all conditions a significant effect of time on arousal ($p_s<0.001$; $\eta^2_{ps}>0.17$). Similar ANOVAs on perceived pleasure revealed only in C20 a significant decrease over time ($p=0.008$, $\eta^2_p=0.13$) with no differences from Pre to Post in other duration conditions ($p_s>0.123$; $\eta^2_{ps}<0.03$). Further separate ANOVAs on perceived stress showed in C10, C15 and C20 a significant effect of time ($p_s=0.001$; $\eta^2_{ps}>0.14$) with no differences from Pre to Post in C5 ($p=0.109$, $\eta^2_p=0.03$).

Further ANOVAs on delta scores (Post − Pre) of control variables revealed an effect of duration (with medium effect size) on stress (F (3, 101) = 2.58, $p=0.058$, $\eta^2_p=0.07$), but no significant effects on arousal (F (3, 101) = 0.78, $p=0.504$, $\eta^2_p=0.02$) or pleasure (F (3, 101) = 0.14, $p=0.936$, $\eta^2_p=0.00$). As concerns the effect of duration on stress, Bonferroni-adjusted pairwise comparisons showed that C20 was perceived as more stressful than C5 ($p=0.058$, $\eta^2_p=0.06$), whereas other conditions were perceived as equally stressful ($p_s>$ 0.182, $\eta^2_{ps}<0.04$; see Appendix S3). The difference in perceived stress among conditions was paralleled by enjoyment data (duration: F (3, 101) = 4.10, $p=0.009$, $\eta^2_p=0.11$), which showed that C20 was perceived as less enjoyable than C5 ($p=0.004$, $\eta^2_p=0.11$) and C10 ($p=0.074$, $\eta^2_p=0.06$), whereas other conditions were perceived as equally enjoyable ($p_s>0.136$, $\eta^2_{ps}<$ 0.05).

3.3 | Cognitive measures

3.3.1 | Effects of duration on executive control, alerting, orienting, and their interactions

A first ANOVA on RTs revealed the classic cue (F(3,101) = 411.62, $p<0.001$, $\eta^2_p=0.92$), flanker (F (1, 103) = 589.93, $p<0.001$, $\eta^2_p=0.85$) and cue × flanker effects (F (3, 101) = 37.03, $p<0.001$, $\eta^2_p=0.52$), which are well known in the literature.[14]

As regard the first two aims, a significant effect of duration on overall RTs with a medium to large effect (F (3, 101) = 4.04, $p=0.009$, $\eta^2_p=0.11$), but no further interaction effects of duration with flanker (i.e., the effect of duration on executive control; F (3, 101) = 0.21, $p=0.890$, $\eta^2_p=0.01$), cue (i.e., the effect of duration on alerting and orienting; F (3, 101) = 0.91, $p=0.520$, $\eta^2_p=0.08$), or cue × flanker (i.e., the effect of duration on attention networks' interactions; F(9, 95) = 0.86, $p=0.560$, $\eta^2_p=0.08$) emerged. Results show

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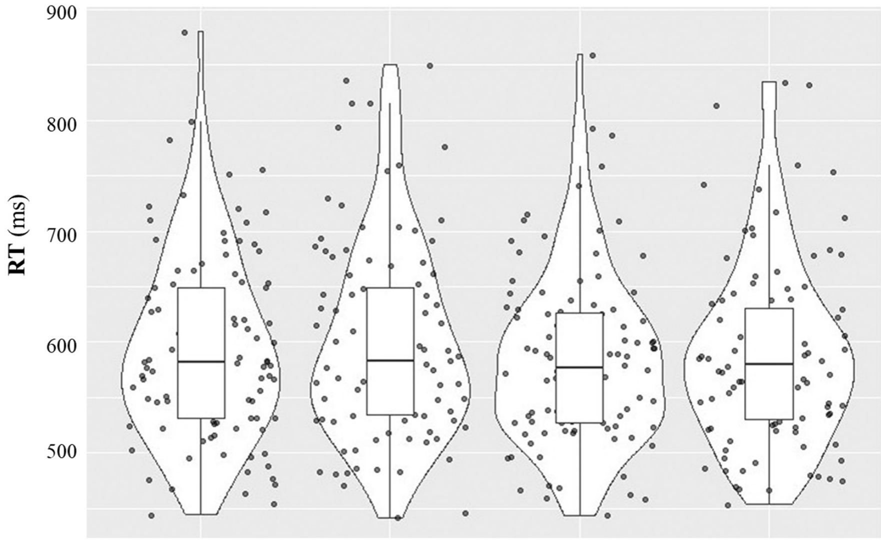

C5	C10	C15	C20
M (*SE*)	*M* (*SE*)	*M* (*SE*)	*M* (*SE*)
593.93 (8.1)	599.18 (8.7)	584.29 (7.6)	588.17 (8.0)

FIGURE 2 Effects of duration on overall reaction times (RTs). *Note*: Duration: $F(3, 101) = 4.04$, $p = 0.009$, $\eta^2_p = 0.11$. C5 = 5 min condition, C10 = 10 min condition, C15 = 15 min condition, C20 = 20 min condition. Results of post-hoc comparisons (significant results bolded): C5 vs. C10: $p = 1.00$, $\eta^2_p = 0.01$. C5 vs. C15: $p = 0.310$, $\eta^2_p = 0.04$. C5 vs. C20: $p = 1.00$, $\eta^2_p = 0.01$. **C10 vs. C15: $p = 0.019$, $\eta^2_p = 0.09$**. C10 vs. C20: $p = 0.210$, $\eta^2_p = 0.04$. C15 vs. C20: $p = 1.00$, $\eta^2_p = 0.01$.

that the duration condition influenced subsequent overall RTs, but not specifically attention network performances and interactions. Post hoc Bonferroni-adjusted pairwise comparisons revealed significant faster RTs after C15 compared to C10 ($p = 0.019$, $\eta^2_p = 0.09$), with small to medium effect size differences between C5 and C15 ($p = 0.310$, $\eta^2_p = 0.04$) and C10 and C20 ($p = 0.211$, $\eta^2_p = 0.04$; see Figure 2), but no differences between C5 and C10 and between C15 and C20 ($p_s = 1.00$, $\eta^2_{ps} = 0.01$). There were no effects of duration for accuracy (duration: $p = 0.952$, $\eta^2_p = 0.00$; duration × flanker: $p = 0.439$, $\eta^2_p = 0.03$; duration × cue: $p = 0.451$, $\eta^2_p = 0.09$; duration × cue × flanker: $p = 0.775$, $\eta^2_p = 0.06$).

3.3.2 | Moderating role of individual characteristics

ANOVAs on RT differences with dichotomized individual characteristics as between-subject factors revealed only for habitual physical activity level and only for the RT difference reflecting the interaction between executive control and spatial disengaging (component of orienting) a significant interaction effect of duration ($F(3, 100) = 4.81$, $p = 0.004$, $\eta^2_p = 0.13$).[‡] Subsequent ANOVAs run on these RT differences, separately for children with lower and higher habitual physical activity levels, revealed only for children with higher physical activity levels a significant effect of duration ($F(3, 46) = 3.15$, $p = 0.034$, $\eta^2_p = 0.17$). Post hoc Bonferroni-adjusted pairwise comparisons revealed lower disengaging costs for executive control after C15 compared to C5 ($p = 0.040$, $\eta^2_p = 0.08$) with no further differences among conditions ($p_s > 0.060$, $\eta^2_{ps} < 0.04$). To interpret this result in children with higher habitual physical activity levels, the difference between flanker effect under invalid spatial cue conditions and double cue conditions were computed separately. As indicated in Figure 3, after C15 lower disengaging costs for executive control resulted from faster RTs after invalid spatial cue conditions (decreasing dark orange bars, Figure 3), whereas after double cue conditions RTs remained stable among conditions (light orange bars, Figure 3). Same analyses performed on accuracy data were not significant ($p > 0.060$, $\eta^2_p < 0.07$).

No further interaction effects of duration with dichotomized individual characteristics emerged neither on RTs nor accuracy values reflecting executive control, alerting, orienting performances and their interactions ($ps > 0.170$, $\eta^2_{ps} < 0.05$).

4 | DISCUSSION

The first aim of the present study was to investigate the dose–response relation between different durations of a cognitively high-challenging bout of physical exercise (5, 10, 15, 20 min) and children's executive control performance. The second aim was to test executive control performance from an attention network perspective to

[‡]An anonymous reviewer validly pointed out, that dichotomization of continuous variables may incur potential difficulties. Thus, we performed subsequent multi-level analyses also with continuous individual variables. Results show similar trends for continuous as for dichotomized variables. Specifically, even if the interaction effect of bout duration and habitual physical activity level on the interactive functioning of executive control and spatial disengaging did not reach significance ($p = 0.056$), results show a significant post-hoc difference between C15 and C5 ($p = 0.006$), indicating that RT differences decreased with increasing habitual physical activity level.

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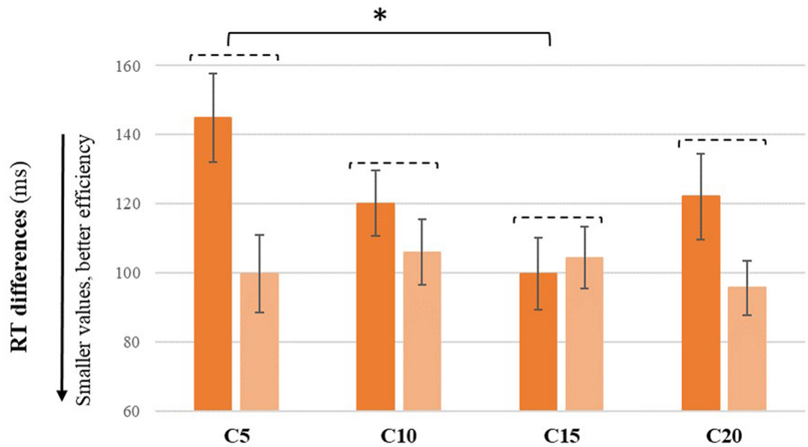

	C5	C10	C15	C20
	M (*SE*)	*M* (*SE*)	*M* (*SE*)	*M* (*SE*)
Invalid spatial cue	144.90 (12.85)	120.19 (9.58)	99.84 (10.42)	122.10 (12.39)
Double cue	99.82 (11.27)	106.00 (9.43)	104.42 (9.03)	95.71 (7.86)

FIGURE 3 Effects of duration on the interaction of executive control (flanker effect) and orienting (spatial attention disengagement) in children with higher habitual physical activity levels. *Note*: C5 = 5 min condition, C10 = 10 min condition, C15 = 15 min condition, C20 = 20 min condition. Dark orange bars = flanker effect under invalid spatial cue conditions, computed as (Invalid spatial cue, flanker incongruent – Invalid spatial cue, flanker congruent). Light orange bars = flanker effect under double cue conditions, computed as (Double cue, flanker incongruent – Double cue, flanker congruent). Error bars represent the standard error of the mean. The interaction of executive control and disengaging is represented by differences between dark orange and light orange bars (dotted lines). Duration effect: $F(3, 46) = 3.15$, $p = 0.034$, $\eta^2_p = 0.17$. Significant difference: *C5 vs. C15: $p = 0.040$, $\eta^2_p = 0.08$. RT, reaction time.

further our understanding of acute exercise duration effects on the efficiency of executive control along and interacting with alerting and orienting attention networks. Finally, we explored if an optimal exercise duration varies according to individual characteristics. In sum, the 15 min bout of physical exercise benefited children's overall information processing speed the most, whereas the efficiency of executive control and other attention networks (alerting and orienting) was unaffected by the duration of the bout. However, exercise duration affected the interactive functioning of executive control and orienting networks in more active children, suggesting that the dose–response relation of interest may be moderated by children's habitual physical activity level. Specifically, more active children seem better able to capitalize on an optimal (15 min) acute exercise duration for maintaining executive control efficiency also under more complex spatial attention conditions.

The present study is the first to directly compare the acute effects of different durations of a cognitively challenging bout of physical exercise on children's executive control and on its functioning in interaction with other attention networks. Regarding the primary aim of the study, executive control performance was not differentially affected by the employed durations, which instead showed differential effects on overall RTs only, in line with previous acute exercise research with adolescents.[20] Indeed, the fine-grained analysis of different durations between 5 and 20 min allowed identifying the duration (15 min), within the intermediate range, that benefited information processing speed the most. In detail, children became faster while maintaining a high response accuracy, thus suggesting a benefit for RTs without a speed-accuracy trade-off effect. This likely reflects the transient biochemical and neurophysiological changes that underlie altered psychological states, such as increased arousal, which facilitate performance in subsequent cognitive tasks.[5]

As regard duration effects in acute exercise studies, to the best of our knowledge, only two studies manipulated the duration of an acute bout of physical exercise and provided evidence on information processing speed.[20,44] However, the different duration and intensity employed, as well as the participants' ages, limit the comparability. In an adult study, superior performance was found after a 20 min moderate intensity bout compared to 10 and 45 min durations.[44] In an adolescent study, 30 min of acute high-intensity intermittent physical exercise improved information processing to a greater extent compared to a 60 min bout of comparable intensity.[20] Inconsistencies of the present findings with those of the abovementioned studies might be due to three factors. (a) The exercise duration identified for adults and adolescents might not fit for children, who have lower cognitive and motor developmental and/or skill levels[11] and are therefore more sensitive to exercise-induced effects.[4] (b) The duration of the acute bout is inherently tied and inversely related to the

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intensity, such that as the intensity of the bout increases, the potential maximum duration decreases.[3] (c) Not physical intensity or cognitive engagement individually, but their interaction determines the overall dose, which may influence the optimal bout duration.[11]

The lack of duration-dependent effects on executive control in the present study adds evidence to previous acute exercise research with children and adolescents, failing to find effects of duration on EFs after a 5–20 min moderate to vigorous classroom-based exercise,[19,21] or after a 10–30 min moderate cycling activity.[22] However, the choice of different combinations of exercise characteristics (intensity, duration, and modality), participants' age, and differences in study design and statistical analyses in the available studies hinder a thorough comparison. Howie and colleagues[21] used separate analyses for the different exercise durations, thus not comparing effects across conditions. Van den Berg et al.[22] compared the effects of different durations in adolescents. Their employed exercise durations, intensities, and cognitive assessment instruments were similar to those used in the current study but without a deliberate inclusion of cognitive challenge. According to the cognitive stimulation hypothesis, cognitively challenging physical exercise that includes cognitive engagement along with physical exertion preactivates similar neural areas associated with EFs, and is therefore thought to have stronger effects on subsequent cognitive performance than a physically demanding exercise with low cognitive engagement.[8] However, the lack of differential duration effects of cognitively challenging bouts of physical exercise on children's EFs does not add further nuances to this hypothesis in regard to exercise duration effects. Instead, our results extend the insensitivity of EFs to acute exercise duration from simply aerobic[22] to also cognitively high-challenging bouts of physical exercise at moderate intensity (with 5 min increments from 5 to 20 min), and from adolescence to childhood. To date, only Graham et al.[19] manipulated the cognitive challenge while investigating the effects of exercise duration on adolescent's EFs. However, unbalanced sampling problems were indicated as a factor that limited the possibility to draw conclusions on the interactive effect of exercise duration and cognitive challenge.

Concerning the second aim of the study, results showed no effects of duration on alerting, orienting, nor on their interaction with the executive control network. This is in line with the lack of differential effects reported in van den Berg et al.'s[22] acute exercise study with adolescents that used the attention network paradigm and investigated the dose–response relation by means of different bout durations of physical exercise (10, 20, or 30 min). However, to the best of our knowledge, neither this,[22] nor other previous exercise studies considered the interaction between attention networks as we did in the present study. Intriguingly, we found evidence of this interaction, which was constrained by the moderating role of children's habitual physical activity level.

Besides the interplay of exercise characteristics, also individual characteristics need to be considered as potential moderators of the effects of bout duration on executive control and other attention networks.[4,7,36,37] The current study included a third exploratory aim to address this issue. Results showed that among environmental, developmental, physical, and cognitive characteristics tested, only habitual physical activity level moderated the effects of duration. Interestingly, habitual physical activity and bout duration jointly affected the interactive performance of the executive control and orienting networks. In general, previous attention network research consistently showed that executive control is worse when spatial attention resources cannot be validly allocated in advance.[14] In our subsample of more active children, this disadvantage in executive control when spatial attentional resources were invalidly allocated was lowest after the 15 min bout of physical exercise. This suggests that children with higher habitual physical activity are better able to capitalize on the cognitive benefits of a 15 min bout of cognitively challenging physical exercise to improve the interactive functioning of their attention networks. In particular, they seem better able to maintain executive control efficiency also when misleading information of invalid spatial cues challenges the orienting network to perform spatial disengagement. This result is consistent with a previous acute cognitively challenging exercise study, suggesting that cognitively challenging bouts of physical exercise benefit only EFs efficiency of children who are physically and cognitively better equipped to capitalize on it.[30] Thus, it seems that only children who are habitually active might be better able to allocate the enhanced attentional resources to the most complex executive task demands (i.e., executive control under disadvantageous spatial conditions), supporting previous evidence on differential effects based on individual characteristics.[4,7,36,37]

In the current study, the four experimental conditions were designed to differ in duration (5, 10, 15, 20 min), but not in cognitive challenge (constantly adapted to the individual ongoing performance) nor in physical intensity (at 65% HR_{max}). Even when the cognitive challenge and physical intensity were held constant, subjective ratings indicated that children perceived the 15 and 20 min conditions as more cognitively and physically demanding than the 5 min condition. However, they did not perceive differences between 5 and 10 min durations and between 15 and 20 min durations. Future research might further

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investigate duration and intensity thresholds in perceived cognitive engagement and physical exertion during physical exercise.

The exergaming task allowed for individualization and constant modulation of the cognitive challenge based on children's ongoing performance, thus ensuring playing at an optimal challenge point. However, the 20 min condition was perceived as more stressful than the 5 min one, as well as less enjoyable than the two shortest conditions. This result is consistent with a previous acute cognitively challenging physical exercise study with children showing a reduction in positive affect after a 20 min bout at moderate to vigorous intensity.[28] Considering that the effects of acute exercise on positive affect may enhance cognitive performance,[27] future research should manipulate affective responses during cognitively challenging bouts of physical exercise. This may further our understanding of mediators that influence the acute exercise-cognition relation and account for interindividual heterogeneity in response to acute exercise.[1]

4.1 | Limitations

The present study is not without limitations. First, the four durations of acute cognitively challenging physical exercise were completed in a counterbalanced order, but without a sedentary control group. This allowed identifying exercise duration effects (first aim of the study), but hindered disentangling physical exercise and duration related effects. Moreover, due to time constraints posed by schools, we did not include a pre-test assessment for cognition. Future studies should include a sedentary control group and utilize a within-subjects crossover pre- and post-test design. In this design, all participants engage in both the exercise and sedentary control conditions in a counterbalanced order. Thus, individual differences and learning/practice effects can be controlled.[3] Second, according to the cognitive stimulation hypothesis,[8] exercise demands were specifically designed to mirror the attention network paradigm. It remains unclear if, beside near transfer effects of exergaming demands on attention network performances, also far transfer effects on other EFs can be elicited. Future studies should evaluate exercise effects on a variety of more and less distant EF measures to investigate transfer effects, and complement these by multiple levels of analysis (e.g., neuroimaging) to understand the neurobiological mechanisms that drive the changes in behavioral performance.[47] Third, given that a child-adapted version of ANT-R with longer stimulus duration and longer interstimulus interval was used as outcome measure, it is possible that effects were biased toward RTs. As indicated by a recent comprehensive review,[3] selective effects on RTs and accuracy might be due to different task parameters or instructions. Accordingly, tasks with long stimulus duration and long interstimulus interval may bias improvements to manifest within RTs[3] and even small differences in task instruction may lead to large differences in participants' strategies.[48] Future studies are needed to systematically investigate the sensitivity of acute cognitively challenging exercise on children's RTs and accuracy. Therefore, for example, various outcome measures with longer and shorter stimulus durations and interstimulus intervals could be compared.

5 | CONCLUSIONS

The present study produced two main novel findings. Firstly, an acute, 15 min bout of cognitively challenging physical exercise transiently benefited children's information processing speed, with no duration-dependent effects for executive control, alerting and orienting performances and interactions. Secondly, a nuanced pattern of duration-dependent effects on the interactive functioning of executive control and orienting networks emerged for children with higher levels of habitual physical activity. Only for more active children, the 15 min bout of physical exercise enhanced the efficiency of executive control, also when spatial attention resources could not be validly allocated in advance. Taken together, results support a dose–response relation of different durations of acute cognitively challenging physical exercise on basic cognitive processes (e.g., information processing), rather than on more complex executive control and attention processes,[4] and for more active children only, on the interactive functioning of executive control and orienting networks.

6 | PERSPECTIVE

The current results call for more refined study designs tailored to address the interplay between individual characteristics and task characteristics of acute bouts of cognitively challenging physical exercise. Furthermore, they highlight the importance of expanding cognitive outcome measures toward assessment paradigms that allow evaluating exercise effects not only on single cognitive functions but also on the interplay of brain networks that better reflect their intertwined functioning under ecological conditions. Results of such research may be used to design practical activities in ecological settings, as active breaks in the school setting, in which learning outcomes are influenced by the individual and interactive functioning of attention networks.

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AUTHOR CONTRIBUTIONS

Conception or design of the work: MS, SA, VB; acquisition of data: SA; data analysis: SA, VB, CZ, JS; interpretation of data for the work: SA, VB, MS; draft of the work: SA, VB, MS, CZ, ALMN. All co-authors revised the work critically for important intellectual content and approved the final version of the manuscript. Furthermore, all co-authors are accountable for all aspects of the work ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved.

ACKNOWLEDGMENTS

We would like to thank the participating teachers, parents and children, as well as the students who helped collecting data and Amie Wallman-Jones for language editing. Open access funding provided by University of Bern.

FUNDING INFORMATION

This study was supported by the Swiss National Science Foundation (Eccellenza grant number: 181074).

CONFLICT OF INTEREST STATEMENT

The authors do not have any conflicts of interest. The results of the study are presented clearly, honestly, and without fabrication, falsification, or inappropriate data manipulation.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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REFERENCES

1. Herold F, Törpel A, Hamacher D, et al. Causes and consequences of interindividual response variability: A call to apply a more rigorous research design in acute exercise-cognition studies. *Front Physiol*. 2021;12:682891.
2. Chang YK, Labban JD, Gapin JI, Etnier JL. The effects of acute exercise on cognitive performance: a meta-analysis. *Brain Res*. 2012;1453:87-101.
3. Pontifex MB, McGowan AL, Chandler MC, et al. A primer on investigating the after effects of acute bouts of physical activity on cognition. *Psychol Sport Exerc*. 2019;40:1-22.
4. Ludyga S, Gerber M, Brand S, Holsboer-Trachsler E, Puhse U. Acute effects of moderate aerobic exercise on specific aspects of executive function in different age and fitness groups: A meta-analysis. *Psychophysiology*. 2016;53(11):1611-1626.
5. Lubans DR, Leahy AA, Mavilidi MF, Valkenborghs SR. Physical activity, fitness, and executive functions in youth: Effects, moderators, and mechanisms. *Curr Top Behav Neurosci*. 2022;53:103-130.
6. Pesce C. Shifting the focus from quantitative to qualitative exercise characteristics in exercise and cognition research. *J Sport Exerc Psychol*. 2012;34(6):766-786.
7. Pesce C. An integrated approach to the effect of acute and chronic exercise on cognition: the linked role of individual and task constraints. In: McMorris T, Tomporowski PD, Audiffren M, eds. *Exercise and Cognitive Function*. Wiley-Heinrich; 2009:213-226.
8. Best JR. Effects of physical activity on children's executive function: Contributions of experimental research on aerobic exercise. *Dev Rev*. 2010;30(4):331-351.
9. Álvarez-Bueno C, Pesce C, Cavero-Redondo I, Sánchez-López M, Martínez-Hortelano JA, Martínez-Vizcaíno V. The effect of physical activity interventions on children's cognition and metacognition: A systematic review and meta-analysis. *J Am Acad Child Adolesc Psychiatry*. 2017;56(9):729-738.
10. Paschen L, Lehmann T, Kehne M, Baumeister J. Effects of acute physical exercise with low and high cognitive demands on executive functions in children: A systematic review. *Pediatr Exerc Sci*. 2019;31(3):267-281.
11. Schmidt M, Egger F, Anzeneder S, Benzing V. Acute cognitively challenging physical activity to promote children's cognition. In: Bailey R, ed. *ICSSPE perspectives. Physical Activity and Sport During the First Ten Years of Life: Multidisciplinary Perspectives*. Routledge; 2021:141-155.
12. Lezak MD. *Neuropsychological Assessment*. Oxford University Press; 1995.
13. Diamond A. Executive functions. *Annu Rev Psychol*. 2013;64:135-168.
14. Fan J, Gu X, Guise KG, et al. Testing the behavioral interaction and integration of attentional networks. *Brain Cogn*. 2009;70(2):209-220.
15. Petersen SE, Posner MI. The attention system of the human brain: 20 years after. *Annu Rev Neurosci*. 2012;35:73-89.
16. de Greeff JW, Bosker RJ, Oosterlaan J, Visscher C, Hartman E. Effects of physical activity on executive functions, attention and academic performance in preadolescent children: A meta-analysis. *J Sci Med Sport*. 2018;21(5):501-507.
17. Verburgh L, Königs M, Scherder EJA, Oosterlaan J. Physical exercise and executive functions in preadolescent children, adolescents and young adults: A meta-analysis. *Br J Sports Med*. 2014;48(12):973-979.
18. Moreau D, Chou E. The acute effect of high-intensity exercise on executive function: A meta-analysis. *Perspect Psychol Sci*. 2019;14(5):734-764.
19. Graham JD, Bremer E, Fenesi B, Cairney J. Examining the acute effects of classroom-based physical activity breaks on executive functioning in 11- to 14-year-old children: Single and additive moderation effects of physical fitness. *Front Pediatr*. 2021;9:688251.
20. Hatch LM, Dring KJ, Williams RA, Sunderland C, Nevill ME, Cooper SB. Effect of differing durations of high-intensity

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intermittent activity on cognitive function in adolescents. *Int J Environ Res Public Health*. 2021;18(21):11594.
21. Howie EK, Schatz J, Pate RR. Acute effects of classroom exercise breaks on executive function and math performance: A dose-response study. *Res Q Exerc Sport*. 2015;86(3):217-224.
22. van den Berg V, Saliasi E, Jolles J, de Groot RHM, Chinapaw MJM, Singh AS. Exercise of varying durations: No acute effects on cognitive performance in adolescents. *Front Neurosci*. 2018;12:672.
23. Benzing V, Heinks T, Eggenberger N, Schmidt M. Acute cognitively engaging exergame-based physical activity enhances executive functions in adolescents. *PLoS One*. 2016;11(12):e0167501.
24. Budde H, Voelcker-Rehage C, Pietraßyk-Kendziorra S, Ribeiro P, Tidow G. Acute coordinative exercise improves attentional performance in adolescents. *Neurosci Lett*. 2008;441(2):219-223.
25. Flynn RM, Richert RA. Cognitive, not physical, engagement in video gaming influences executive functioning. *J Cogn Dev*. 2018;19(1):1-20.
26. Jäger K, Schmidt M, Conzelmann A, Roebers CM. Cognitive and physiological effects of an acute physical activity intervention in elementary school children. *Front Psychol*. 2014;5:71.
27. Schmidt M, Benzing V, Kamer M. Classroom-based physical activity breaks and children's attention: Cognitive engagement works! *Front Psychol*. 2016;7:1474.
28. Bedard C, Bremer E, Graham JD, Chirico D, Cairney J. Examining the effects of acute cognitively engaging physical activity on cognition in children. *Front Psychol*. 2021;12:653133.
29. Best JR. Exergaming immediately enhances children's executive function. *Dev Psychol*. 2012;48(5):1501-1510.
30. Jäger K, Schmidt M, Conzelmann A, Roebers CM. The effects of qualitatively different acute physical activity interventions in real-world settings on executive functions in preadolescent children. *Ment Health Phys Act*. 2015;9:1-9.
31. van den Berg V, Saliasi E, de Groot RHM, Jolles J, Chinapaw MJM, Singh AS. Physical activity in the school setting: Cognitive performance is not affected by three different types of acute exercise. *Front Psychol*. 2016;7:723.
32. Egger F, Conzelmann A, Schmidt M. The effect of acute cognitively engaging physical activity breaks on children's executive functions: Too much of a good thing? *Psychol Sport Exerc*. 2018;36:178-186.
33. Gallotta MC, Guidetti L, Franciosi E, Emerenziani GP, Bonavolontà V, Baldari C. Effects of varying type of exertion on children's attention capacity. *Med Sci Sports Exerc*. 2012;44(3):550-555.
34. Gallotta MC, Emerenziani GP, Franciosi E, Meucci M, Guidetti L, Baldari C. Acute physical activity and delayed attention in primary school students. *Scand J Med Sci Sports*. 2015;25(3):331-338.
35. Wen X, Yang Y, Wang F. Influence of acute exercise on inhibitory control and working memory of children: A comparison between soccer, resistance, and coordinative exercises. *Int J Sport Psychol*. 2021;52(2):101-119.
36. Pesce C, Ballester R, Benzing V. Giving physical activity and cognition research 'some soul': Focus on children and adolescents. *Eur J Hum Mov*. 2021;47:1-7.
37. Ishihara T, Drollette ES, Ludyga S, Hillman CH, Kamijo K. The effects of acute aerobic exercise on executive function: A systematic review and meta-analysis of individual participant data. *Neurosci Biobehav Rev*. 2021;128:258-269.
38. Haverkamp BF, Wiersma R, Vertessen K, van Ewijk H, Oosterlaan J, Hartman E. Effects of physical activity interventions on cognitive outcomes and academic performance in adolescents and young adults: A meta-analysis. *J Sports Sci*. 2020;38(23):2637-2660.
39. Posner MI, Rothbart MK. Attention to learning of school subjects. *Trends Neurosci Educ*. 2014;3(1):14-17.
40. Chang YK, Pesce C, Chiang YT, Kuo CY, Fong DY. Antecedent acute cycling exercise affects attention control: An ERP study using attention network test. *Front Hum Neurosci*. 2015;9:156.
41. Benzing V, Schmidt M. Exergaming for children and adolescents: Strengths, weaknesses, opportunities and threats. *J Clin Med*. 2018;7(11):422.
42. Martin-Niedecken AL, Mahrer A, Rogers K, de Bruin ED, Schättin A. "HIIT" the ExerCube: Comparing the effectiveness of functional high-intensity interval training in conventional vs. exergame-based training. *Front Comp Sci*. 2020;2:33.
43. McMorris T, Hale BJ. Differential effects of differing intensities of acute exercise on speed and accuracy of cognition: A meta-analytical investigation. *Brain Cogn*. 2012;80(3):338-351.
44. Chang YK, Chu CH, Wang CC, et al. Dose-response relation between exercise duration and cognition. *Med Sci Sports Exerc*. 2015;47(1):159-165.
45. Anzeneder S, Zehnder C, Martin-Niedecken AL, Schmidt M, Benzing V. Acute exercise and children's cognitive functioning: What is the optimal dose of cognitive challenge? *Psychol Sport Exerc*. 2023;66:102404.
46. Macleod JW, Lawrence MA, McConnell MM, Eskes GA, Klein RM, Shore DI. Appraising the ANT: Psychometric and theoretical considerations of the Attention Network Test. *Neuropsychology*. 2010;24(5):637-651.
47. Herold F, Wiegel P, Scholkmann F, Müller NG. Applications of functional near-infrared spectroscopy (fNIRS) neuroimaging in exercise-cognition science: A systematic, methodology-focused review. *J Clin Med*. 2018;7(12):466.
48. Themanson JR, Pontifex MB, Hillman CH. Fitness and action monitoring: Evidence for improved cognitive flexibility in young adults. *Neuroscience*. 2008;157(2):319-328.

SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

How to cite this article: Anzeneder S, Zehnder C, Schmid J, Martin-Niedecken AL, Schmidt M, Benzing V. Dose–response relation between the duration of a cognitively challenging bout of physical exercise and children's cognition. *Scand J Med Sci Sports*. 2023;33:1439-1451. doi:10.1111/sms.14370

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Appendix S1.

Background variables

Beside *age, biological sex* and *writing hand*, the *body weight* and *height* were measured according to standardized protocols with children wearing regular clothes without shoes. *Body Mass Index* (BMI) was calculated [weight (kg)/ height (m)^2]. *Socioeconomic status*[49] was assessed using the Family Affluence Scale III. This consists of six questions about the family (e.g., whether they have their own bedroom or number of family-owned computers). The response format varies by item and points are given for a higher number, for example of computers. The prosperity index is then calculated as the sum of the points on the six items. An acceptable reliability and validity has been demonstrated[49]. *Pubertal developmental status* was assessed using the German version of the pubertal developmental scale[50]. This consists of three questions for each sex, asking for example: “Have you noticed a deepening of your voice?”. Responses are given on a 4-point Likert scale, scoring 1-4 points (e.g., not yet started; barely started; definitely started; seems complete). The puberty index (3-12 points) is calculated by summing up the scores of the three items. Acceptable reliability and validity has been demonstrated[50]. The *habitual physical activity* was assessed using the German version of the physical activity questionnaire for older children[51]. This 7-day recall instrument consists of 10 items, asking to indicate which physical activities children have performed (item 1), how physically active they were during school hours (items 2-8), and how often they performed a moderate to vigorous activity (item 9). The response format varies by item and points are given for a higher number, for example of performed physical activities. The summary score (1-5 points) is calculated by the mean of items 1-9. Item 10 can be used to identify children who had unusual activity during the previous week. The questionnaire is a valid and reliable measure of children’s physical activity levels[51]. *Weekly videogame practice* was assessed, asking children to indicate how long they played videogames during the last 7 days (in minutes). This questionnaire was self-developed for the purposes of the current study and has not been validated yet. *Need for cognition*, defined as disposition to engage in and enjoy effortful cognitive endeavors[52], was assessed using the German teen version of the Need for Cognition scale[52]. This consists of 19 questions, asking for example: “I would rather do something that requires little thought than something that is sure to challenge my thinking abilities?”. Responses are given on a 5-point Likert scale, scoring 1-5 points (from extremely uncharacteristic of me to extremely characteristic of me). Some items are reverse-scored. The total score (19-95 points) is calculated by summing up the scores of the 19 items. Acceptable reliability and validity have been demonstrated[52]. *Cardiovascular fitness* (Vo^2max) and HR_{max} were assessed by a 20-m Shuttle Run test[53]. All participants wore a Polar H7 HR monitor that was connected to the Polar Team App (Polar Electro Oy, Finland), in which HR data was stored. The test was performed during a regular physical education lesson, under supervision of a physical education teacher. All children were familiar with this test and were encouraged by their teacher and the research team to exert maximum performance. The test had an initial running speed of 8.0 km/h that progressively increased with 0.5 km/h in one-minute stages. The highest completed stage with an accuracy of half a stage was recorded.

Manipulation check

Perceived physical exertion (RPE) was measured using the Borg RPE scale. Acceptable reliability and validity in preadolescents have been provided for this scale[54]. To determine children’s *cognitive engagement* during exergaming, Borg RPE scale was adapted to ask for perceived cognitive engagement (RCE). They had to answer the question, “How exhausting was the previous activity for your brain?”. This adapted version is not a validated instrument, but proved to be feasible with children and adolescents and sensitive to detect changes in cognitive engagement among intervention conditions[23,27,32].

Control variables

In addition to manipulation check variables, different *control variables* with acceptable reliability and validity were assessed. Arousal, pleasure and perceived stress were measured using the single-item pictorial Self-Assessment-Manikin[55]. Enjoyment was assessed with the physical activity enjoyment scale[56].

49. Torsheim T, Cavallo F, Levin KA, et al. Psychometric validation of the revised family affluence scale: A latent variable approach. Child Indic Res 2016; 9(3): 771–84.
50. Watzlawik M. Die Erfassung des Pubertätsstatus anhand der Pubertal Development Scale [Measuring the pubertal status using the Pubertal Developmental Scale]. Diagnostica 2009; 55(1): 55–65.
51. Crocker PRE, Bailey DA, Faulkner RA, Kowalski KC, McGrath R. Measuring general levels of physical activity: Preliminary evidence for the physical activity questionnaire for older children. Med Sci Sports Exerc 1997; 29(10): 1344–9.
52. Preckel F. Assessing need for cognition in early adolescence. Eur J Psychol Assess 2014; 30(1): 65–72.
53. Léger LA, Mercier D, Gadoury C, Lambert J. The multistage 20 meter shuttle run test for aerobic fitness. J Sports Sci 1988; 6: 93–101.
54. Lamb KL. Exercise regulation during cycle ergometry using the children's effort rating table (CERT) and rating of perceived exertion (RPE) scales. Pediatr Exerc Sci 1996; 8(4): 337–50.
55. Bradley MM, Lang PJ. Measuring emotion: The self-assessment manikin and the semantic differential. J Behav Ther Exp Psychiatry 1994; 25(1): 49–59.
56. Jekauc D, Voelkle M, Wagner MO, Mewes N, Woll A. Reliability, validity, and measurement invariance of the German version of the physical activity enjoyment scale. J Pediatr Psychol 2013; 38(1): 104–15.

Appendix S2. ***Exergaming tasks***

ExerCube game setup:

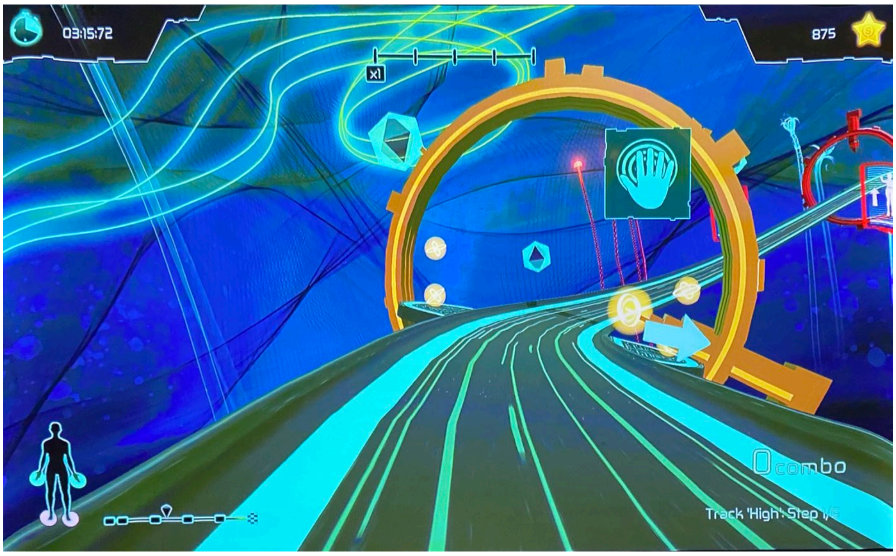
Exergaming video: **https://vimeo.com/759054046**

Exergaming elements in "catching a sideway point" example:

1. First, a cue appears on the right, left or both sides of a colored gate

2. When the gate comes closer, children have to perform a lateral shuffle step and catch a yellow sideway point (other gates can request punches, skipping, jumps, squats or deep lunges).

3. Movements must be performed following the direction of the target arrow, while ignoring the rotation (to the right or to the left) of the central distracting point (can be congruent or incongruent with the arrow direction; in the picture below the central point is congruent)



Examples of movements used to manipulate the cognitive challenge:

Picture 1. ***Punches with congruent stimuli but double (not spatial informative) cue***

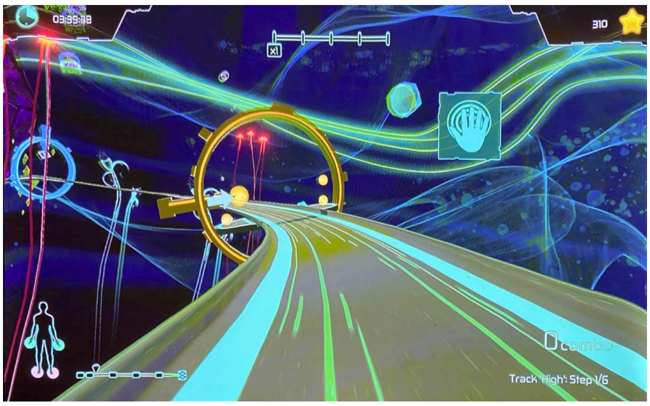
Children's task is to follow the direction of the target arrow (pointing here to the left), while ignoring the rotation of the central quadrangle (here to the left and therefore congruent). The double cue is not spatial informative (fists on both sides).

Picture 2. ***Punches) with distracting stimuli but valid cue***

Children's task is to follow the direction of the target arrow (pointing here to the left), while ignoring the rotation of the central quadrangle (here to the right and therefore incongruent). The cue is valid (fist on the left side).

Picture 3. ***Catching a sideway point with congruent stimuli but misleading cue***

Children's task is to follow the direction of the target arrow (pointing here to the right), while ignoring the rotation of the central point (here to the right and therefore congruent). The cue is misleading (hand on the left side).

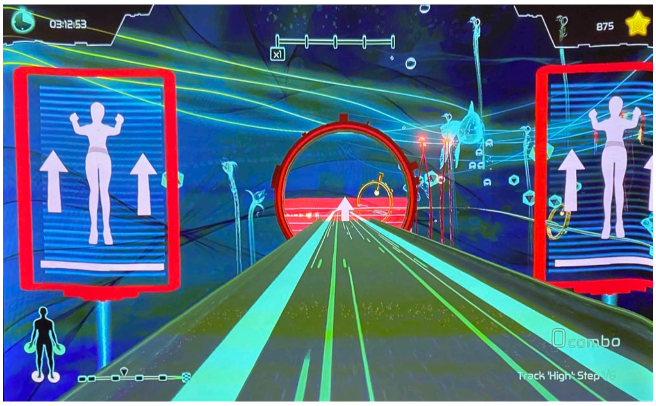


Picture 4. ***Catching a sideway point with distracting stimuli but correct cue***

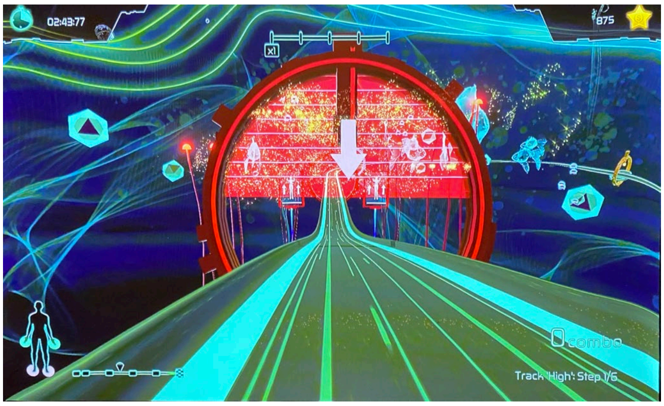
Children's task is to follow the direction of the target arrow (pointing here to the right), while ignoring the rotation of the central point (here to the left and therefore incongruent). The cue is misleading (hand on the right side).

Examples of movements used to maintain children's heart rate constant

Picture 4. *Skipping*



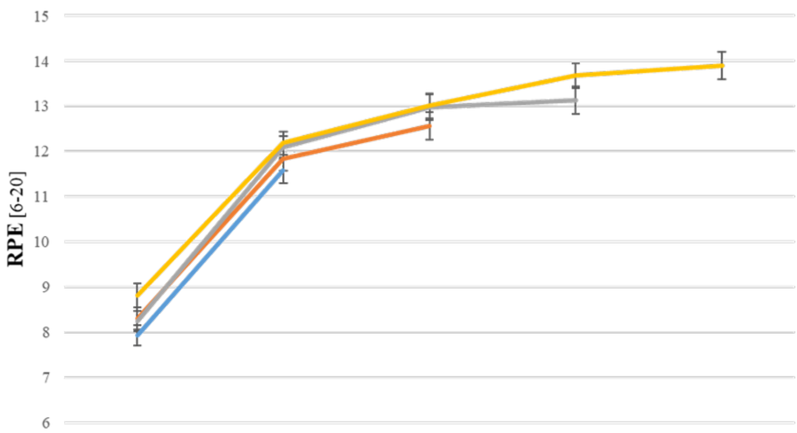
Picture 5. *Jumps*



Picture 6. *Squats*

Appendix S3. ***Statistics of manipulation check and control variables among duration conditions (C5, C10, C15, C20) and time points (T_0, T_1, T_2, T_3, T_4)***

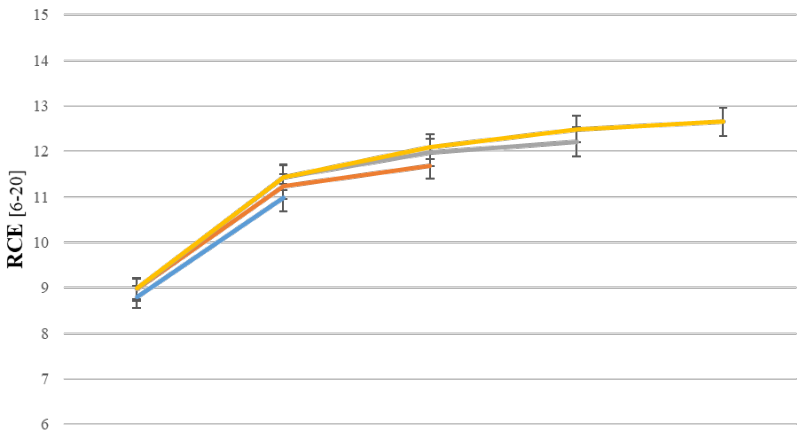
C1. Perceived physical exertion



	T0 (Pre)	T1 (5min)	T2 (10 min)	T3 (15 min)	T4 (20 min)
	M (*SE*)	*M* (*SE*)	*M* (*SE*)	*M* (*SE*)	*M* (*SE*)
C5	7.94 (0.22)	11.58 (0.29)	-	-	-
C10	8.31 (0.24)	11.85 (0.27)	12.57 (0.30)	-	-
C15	8.25 (0.22)	12.09 (0.26)	12.98 (0.28)	13.14 (0.30)	-
C20	8.82 (0.26)	12.19 (0.26)	13.01 (0.28)	13.68 (0.28)	13.89 (0.30)

Note. RPE: rating of perceived exertion. Error bars represent the standard error of the mean. Effect of time: *C5*: $F(1, 103) = 174.02$, $p <.001$, $\eta^2_p = .63$. *C10*: $F(2, 102) = 85.58$, $p <.001$, $\eta^2_p = .63$. *C15*: $F(3, 102) = 74.83$, $p <.001$, $\eta^2_p = .69$. *C20*: $F(4, 100) = 65.08$, $p <.001$, $\eta^2_p = .72$. Effect of duration on delta scores (Post – Pre): $F(3, 101) = 5.16$, $p = .002$, $\eta^2_p = .13$. Results of post-hoc comparisons among delta scores (significant results bolded): C5 vs. C10: $p = .544$, $\eta^2_p = .03$; **C5 vs. C15: $p = .006$, $\eta^2_p = .10$**; **C5 vs. C20: $p = .003$, $\eta^2_p = .11$**; C10 vs. C15: $p = .697$, $\eta^2_p = .02$; C10 vs. C20: $p = .285$, $\eta^2_p = .04$; C15 vs. C20: $p = 1.00$, $\eta^2_p = .00$.

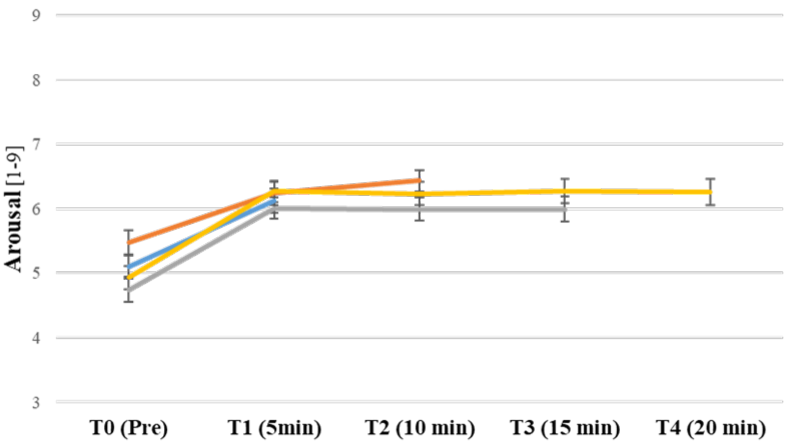
C2. Perceived cognitive engagement



	T0 (Pre)	T1 (5min)	T2 (10 min)	T3 (15 min)	T4 (20 min)
	M (*SE*)	*M* (*SE*)	*M* (*SE*)	*M* (*SE*)	*M* (*SE*)
C5	8.80 (0.25)	10.98 (0.29)	-	-	-
C10	8.97 (0.25)	11.23 (0.27)	11.68 (0.28)	-	-
C15	8.97 (0.24)	11.43 (0.28)	11.98 (0.30)	12.22 (0.33)	-
C20	8.99 (0.23)	11.42 (0.27)	12.10 (0.28)	12.49 (0.29)	12.65 (0.32)

Note. RCE: rating of cognitive engagement. Error bars represent the standard error of the mean. Effect of time: *C5*: $F(1, 103) = 71.06$, $p < .001$, $\eta^2_p = .41$. *C10*: $F(2, 102) = 40.82$, $p < .001$, $\eta^2_p = .45$. *C15*: $F(3, 102) = 45.50$, $p < .001$, $\eta^2_p = .58$. *C20*: $F(4, 100) = 30.32$, $p < .001$, $\eta^2_p = .55$. Effect of duration on delta scores (Post – Pre): $F(3, 101) = 6.02$, $p = .001$, $\eta^2_p = .15$. Results of post-hoc comparisons among delta scores (significant results bolded): C5 vs. C10: $p = .433$, $\eta^2_p = .03$; **C5 vs. C15: $p = .004$, $\eta^2_p = .11$**; **C5 vs. C20: $p = .001$, $\eta^2_p = .13$**; C10 vs. C15: $p = .635$, $\eta^2_p = .03$; C10 vs. C20: $p = .074$, $\eta^2_p = .06$; C15 vs. C20: $p = 1.00$, $\eta^2_p = .01$.

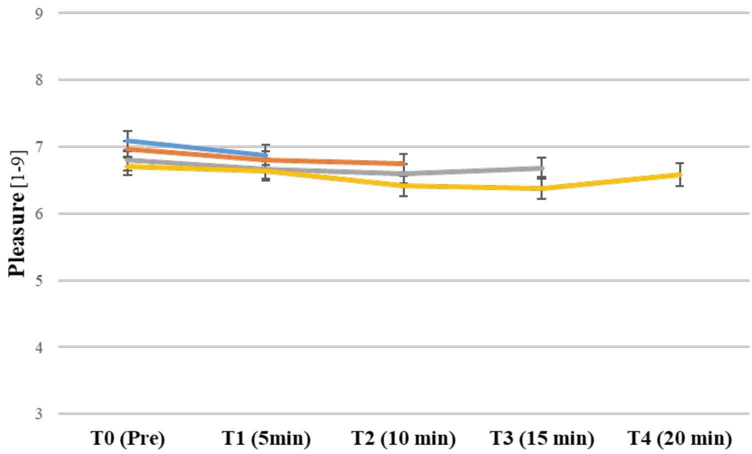
C4. Arousal



	T0 (Pre)	T1 (5min)	T2 (10 min)	T3 (15 min)	T4 (20 min)
	M (*SE*)	*M* (*SE*)	*M* (*SE*)	*M* (*SE*)	*M* (*SE*)
C5	5.10 (0.18)	6.13 (0.19)	-	-	-
C10	5.48 (0.19)	6.24 (0.18)	6.43 (0.17)	-	-
C15	4.75 (0.19)	6.01 (0.17)	5.99 (0.18)	5.99 (0.20)	-
C20	4.93 (0.18)	6.27 (0.17)	6.24 (0.18)	6.28 (0.19)	6.26 (0.20)

Note. Error bars represent the standard error of the mean. Effect of time: *C5*: $F(1, 103) = 33.90$, $p < .001$, $\eta^2_p = .25$. *C10:* $F(2, 102) = 10.42$, $p < .001$, $\eta^2_p = .17$. *C15*: $F(3, 102) = 16.75$, $p < .001$, $\eta^2_p = .33$. *C20*: $F(4, 100) = 18.21$, $p < .001$, $\eta^2_p = .42$. Effect of duration on delta scores (Post – Pre): $F(3, 101) = .79$, $p = .504$, $\eta^2_p = .02$.

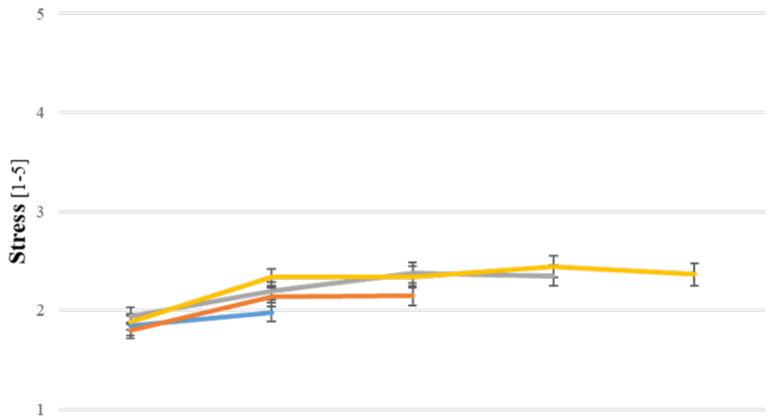
C3. Pleasure



	M (*SE*)	*M* (*SE*)	*M* (*SE*)	*M* (*SE*)	*M* (*SE*)
C5	7.09 (0.15)	6.87 (0.15)	-	-	-
C10	6.96 (0.13)	6.81 (0.13)	6.74 (0.15)	-	-
C15	6.80 (0.15)	6.67 (0.15)	6.59 (0.15)	6.68 (0.15)	-
C20	6.71 (0.14)	6.64 (0.15)	6.41 (0.15)	6.38 (0.16)	6.58 (0.17)

Note. Error bars represent the standard error of the mean. Effect of time: *C5*: $F(1, 103) = 2.42$, $p = .123$, $\eta^2_p = .02$. *C10*: $F(2, 102) = 1.53$, $p = .222$, $\eta^2_p = .03$. *C15*: $F(3, 102) = 1.01$, $p = .394$, $\eta^2_p = .03$. *C20*: $F(4, 100) = 3.63$, $p = .008$, $\eta^2_p = .13$. Effect of duration on delta scores (Post – Pre): $F(3, 101) = .14$, $p = .936$, $\eta^2_p = .00$.

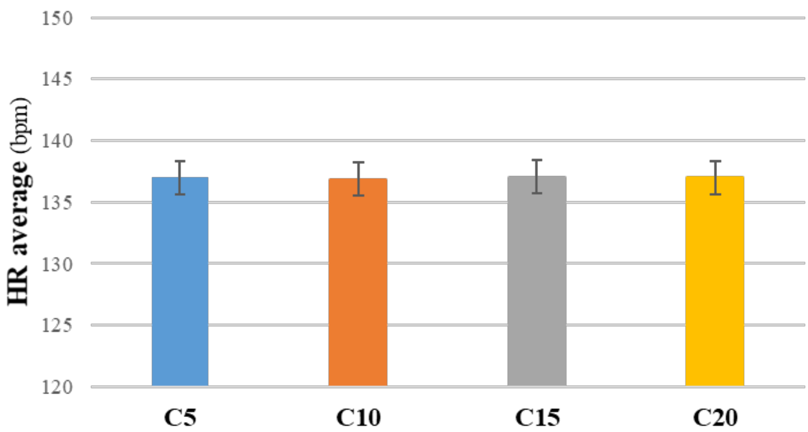
C5. Stress



	T0 (Pre)	T1 (5min)	T2 (10 min)	T3 (15 min)	T4 (20 min)
	M (*SE*)	*M* (*SE*)	*M* (*SE*)	*M* (*SE*)	*M* (*SE*)
C5	1.84 (0.10)	1.98 (0.10)	-	-	-
C10	1.80 (0.08)	2.13 (0.09)	2.14 (0.10)	-	-
C15	1.94 (0.09)	2.19 (0.09)	2.38 (0.10)	2.35 (0.11)	-
C20	1.88 (0.08)	2.33 (0.09)	2.33 (0.11)	2.44 (0.11)	2.36 (0.12)

Note. Error bars represent the standard error of the mean. Effect of time: C5: $F(1, 103) = 2.61$, $p = .109$, $\eta^2_p = .03$. *C10*: $F(2, 102) = 8.08$, $p = .001$, $\eta^2_p = .14$. *C15*: $F(3, 102) = 7.83$, $p < .001$, $\eta^2_p = .19$. *C20*: $F(4, 100) = 8.27$, $p < .001$, $\eta^2_p = .25$. Effect of duration on delta scores (Post – Pre): $F(3, 101) = 2.57$, $p = .058$, $\eta^2_p = .07$. Results of post-hoc comparisons among delta scores (significant result bolded): C5 vs. C10: $p = .481$, $\eta^2_p = .03$; C5 vs. C15: $p = .182$, $\eta^2_p = .04$; **C5 vs. C20: $p = .058$, $\eta^2_p = .06$**; C10 vs. C15: $p = 1.00$, $\eta^2_p = .00$; C10 vs. C20: $p = 1.00$, $\eta^2_p = .01$; C15 vs. C20: $p = 1.00$, $\eta^2_p = .00$.

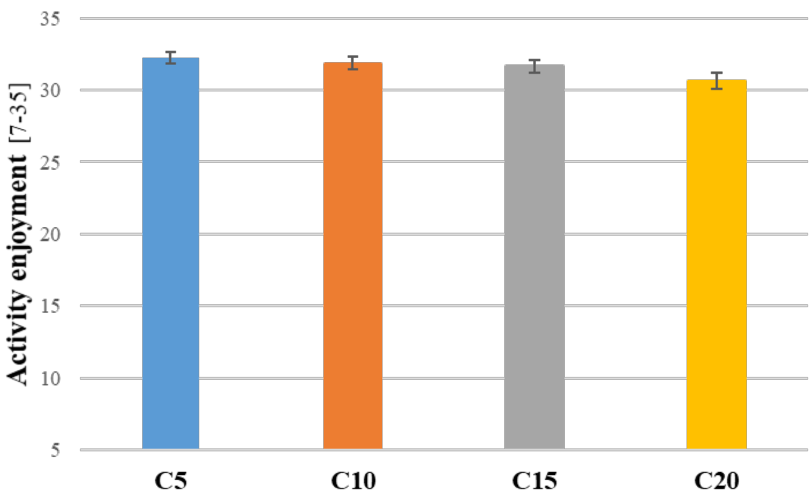
C6. HR average over exergaming time



C5 *M* (*SE*)	C10 *M* (*SE*)	C15 *M* (*SE*)	C20 *M* (*SE*)
136.99 (1.38)	136.88 (1.37)	137.05 (1.37)	136.98 (1.37)

Note. Error bars represent the standard error of the mean. Effect of duration: $F(3, 101) = .99$, $p = .403$, $\eta^2_p = .03$.

C7. Activity enjoyment after the exergaming



C5 *M* (*SE*)	C10 *M* (*SE*)	C15 *M* (*SE*)	C20 *M* (*SE*)
32.22 (0.40)	31.86 (0.43)	31.66 (0.42)	30.65 (0.54)

Note. Error bars represent the standard error of the mean. Effect of duration: $F(3, 101) = 4.10$, $p = .009$, $\eta^2_p = .11$. Results of post-hoc comparisons (significant results bolded): C5 vs. C10: $p = 1.00$, $\eta^2_p = .01$; C5 vs. C15: $p = .374$, $\eta^2_p = .03$; **C5 vs. C20: $p = .004$, $\eta^2_p = .11$**; C10 vs. C15: $p = 1.00$, $\eta^2_p = .00$; **C10 vs. C20: $p = .074$, $\eta^2_p = .06$**; C15 vs. C20: $p = .136$, $\eta^2_p = .05$.

Supplementary material

III

Anzeneder, **S.**, Schmid, J., Zehnder, C., Koch, L., Martin-Niedecken, A. L., Schmidt, M., & Benzing, V. (2024). Acute cognitively challenging exercise as "cognitive booster" for children: Positive feedback matters! *Mental Health and Physical Activity*, *27*, 100621. https://doi.org/10.1016/j.mhpa.2024.100621

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Mental Health and Physical Activity 27 (2024) 100621

Contents lists available at ScienceDirect

Mental Health and Physical Activity

journal homepage: www.elsevier.com/locate/menpa

Acute cognitively challenging exercise as "cognitive booster" for children: Positive feedback matters!

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ARTICLE INFO

Keywords:
Acute physical activity
Exergaming
Cognitive engagement
Affective states
Executive functions
Mental health

ABSTRACT

Background and aim: Acute exercise can enhance children's cognition. Heterogeneous effect sizes necessitate investigating exercise task characteristics, contextual factors, and related affective states. The study aimed to test whether different feedback forms during acute cognitively challenging exercise affect children's executive control, alerting, and orienting performances, also considering the potential mediational role of affective states.
Methods: In a within–subjects posttest only design, 100 children (M_{age} = 11.0, SD_{age} = 0.8, 48% female) participated weekly in one of three exergames with different feedback: no feedback (NO-FB), standard acoustic environment (ST-FB), positive feedback (PO-FB). Acute bouts were designed to keep physical intensity (65% HR_{max}) and duration (15-min) constant and to have a high cognitive challenge. Valence, arousal, perceived physical exertion, cognitive engagement, and flow were assessed before, during and after exergaming. Each bout was followed by an Attention Network Test.
Results: ANOVAs revealed a significant main effect of feedback on executive control ($\eta_p^2 = 0.09$) with faster reaction times after PO-FB compared to the other conditions ($\eta_{ps}^2 > 0.06$) and on valence at post–test ($\eta_p^2 = 0.11$) with highest values in PO-FB ($\eta_{ps}^2 > 0.08$). In PO-FB, valence was associated with executive control ($r = -0.23$) but did not mediate feedback effects on executive control (95% CI [–5.25, 4.68]). Alerting and orienting performances were unaffected by feedback ($\eta_{ps}^2 < 0.08$).
Conclusion: Results suggest that positive feedback during acute cognitively challenging exergaming enhances children's executive control and positive affect, highlighting that exercise task characteristics and contextual factors are essential for cognitive benefits.

1. Introduction

Physical exercise has a variety of well documented positive effects on mental health both in the long–term after prolonged practice (i.e., chronic exercise) and transiently after a single bout (i.e., acute exercise; Petruzzello et al., 2018). In the cognitive domain, acute exercise effects have been mainly investigated on executive functions (EFs; Pontifex et al., 2019) that encompass a range of processes necessary for regulating thoughts, emotions, and actions relevant to learning and daily functioning (Diamond, 2013).

Within EFs, inhibition is by far the most investigated acute exercise outcome across the lifespan (Pontifex et al., 2019). Research with children especially focused on the executive control component of inhibition, that is the ability to exert control over interference (Diamond, 2013), since it plays a crucial role in behavioral skills relevant to learning, such as self–regulation (Liew, 2012). Interestingly, executive control is not only a component of inhibition (Diamond, 2013), but also one of three independent yet interacting attention networks, along with alerting (i.e., achieving and maintaining an alert state to detect sensory inputs) and orienting (i.e., selecting relevant information from sensory inputs; Fan et al., 2009).

Extensive research with children provides evidence of transient improvements of executive control after acute exercise with small to medium effect sizes (De Greeff, Bosker, Oosterlaan, Visscher, & Hartman, 2018; Verburgh et al., 2014). This effect has been attributed to different underlying mechanisms of neurochemical and physiological changes

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https://doi.org/10.1016/j.mhpa.2024.100621
Received 3 January 2024; Received in revised form 19 July 2024; Accepted 21 July 2024
Available online 31 July 2024
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such as increased blood flow, release of catecholamines, neurotrophins, and glucocorticoid levels (Basso & Suzuki, 2017). In addition, these changes are accompanied by altered physiological states such as increased arousal, facilitating cognitive performance by an increased allocation of attention (i.e., arousal theory; Audiffren et al., 2009).

However, there is still a considerable heterogeneity in effect sizes (Lubans et al., 2022), which raises fundamental questions about the effectiveness of exercise in enhancing EFs (Furley et al., 2023). The observed heterogeneity could be attributed to the fact that cognitive outcomes are (interactively) influenced by exercise task characteristics, individual characteristics, contextual factors, and related affective states. Task characteristics may be qualitative as modality and quantitative as intensity and duration (Lubans et al., 2022; Pesce, 2012). Individual characteristics encompass a range of demographic, biological, developmental, physical, and cognitive factors (Herold et al., 2021; Pesce, 2009). Contextual factors refer to the external and situational conditions of exercise, including the social and physical environment (i.e., where and with whom the exercise is performed), the delivery mode (i.e., the way it is delivered such as face–to–face or virtual reality) and the delivery style of the bout (i.e., the instructional style; Pesce et al., 2023; Vella, Aidman, et al., 2023; Vella, Sutcliffe, et al., 2023). The delivery style encompasses feedback forms grounded on theories such as the macro–theory of positive functioning (Stanley & Schutte, 2023) and evidence–based forms like the use of music (Vella, Aidman, et al., 2023).

A qualitative exercise characteristic that has garnered increasing interest is the cognitive demand (Pesce, 2012), which can be inherent such as in team games or deliberately added/incorporated in less challenging repetitive and automatized movement (Herold et al., 2018). Additional cognitive demands are juxtaposed to the physical task demands, meaning that resolving a cognitive task is not necessary to successfully complete the physical task, and vice versa (e.g., stationary cycling while counting). Incorporated cognitive demands are intertwined with the physical task, meaning that resolving a cognitive task is a prerequisite for successfully completing the physical task, and vice versa (e.g., dancing or delayed imitation tasks; Herold et al., 2018). The cognitive engagement elicited by cognitively challenging exercise seem to pre–activate similar brain regions that are used to control higher–-order cognitive processes leading to better performance in subsequent EF tasks (i.e., cognitive stimulation hypothesis; Budde et al., 2008; Pesce, 2012). This mechanism is further supported by the idea of common neural substrates in both complex cognitive and movement tasks: Combining cognitive and physical demands may elicit synergistic effects due to coactivation and inter–connectedness of prefrontal and cerebellar areas (Becker et al., 2023; Serrien et al., 2007).

However, results of acute cognitively challenging bouts on children's EFs are inconsistent, with findings ranging from negative to positive effects (Paschen et al., 2019). Negative effects on specific facets of EFs (Egger et al., 2018) might emerge when the cognitive engagement required by challenging bouts of exercise exceeds the available cognitive resources, leading to depletion (Audiffren & André, 2015). Schmidt et al. (2021) further elaborated on this, suggesting that a curvilinear function linking the degree of cognitive demand to executive control might be responsible for inconsistent findings of studies that dichotomized lower versus higher cognitive demand. Recently, an experimental study addressed this issue in primary school children by employing three levels of cognitive challenge through a specifically designed exergame (i.e., an active videogame; Anzeneder, Zehnder, Martin–Niedecken, et al., 2023). Results indicated best executive control performance after the high–challenging bout.

Exergaming as a tool to incorporate targeted amounts of cognitive demands into physical exercise has shown promise and is spreading in exercise–cognition research across the lifespan (Benzing & Schmidt, 2018; Stojan & Voelcker–Rehage, 2019). Its major advantages for cognitively challenging acute exercise studies are that (a) experimental conditions can be conducted in a highly standardized and ecologically valid fashion in the field; (b) the manipulation of both physical intensity and cognitive demands of the bout can be finely tuned and adapted online to the individual (Benzing & Schmidt, 2018); (c) the delivery style of exergaming encompasses visual, acoustic and/or tactile feedback forms that provide multiple sources of information (Bernardo et al., 2021). This opens the possibility of investigating the single and combined effects of different exercise task characteristics and contextual factors.

One reason for the inconsistent pattern of results from acute cognitively challenging exercise studies may be that previous studies differed in exercise task and individual characteristics, and largely neglected potential mediators in the affective domain that can be influenced by exercise delivery style (Pesce et al., 2023; Vella, Aidman, et al., 2023). This is surprising, considering that enhanced affective states during exercise may transiently benefit subsequent cognitive performance. Indeed, according to the psychological overcompensation hypothesis of the self–control model, an enhanced affective state during exercise may compensate for the depletion of limited self–regulation resources caused by the exercise task itself (Audiffren & André, 2015). From a neurophysiological perspective, positive affective states generated by exercise may transiently modulate the effectiveness of cognitive processes in the prefrontal cortex involved in EFs and self–regulation (i.e., dopaminergic hypothesis; Audiffren & André, 2015). Moreover, specifically in virtual environments, areas of the right dorsolateral prefrontal cortex activated during affect–regulation efforts seem to reduce their activity when virtual reality cues lessen reliance on cognitive efforts to attenuate unpleasant interoceptive sensations associated with physical exercise effort (Jones & Ekkekakis, 2019).

To effectively enhance affective states, evidence–based delivery styles such as music (Terry et al., 2020) or theory–driven delivery styles such as positive feedback (Fransen et al., 2018) have been proposed. The effectiveness of music is based on synchronization and distraction theories, postulating that music synchronized with movements can increase perceived arousal (Bigliassi et al., 2018) or reduce perceived physical exertion by shifting attention toward external environmental cues (Fritz et al., 2013), respectively. The effectiveness of positive feedback can be explained in the light of the macro–theory of positive functioning that integrates self–determination (Ryan & Deci, 2000) and 'broaden and build' theories (Fredrickson, 2004). According to this macro–theory, higher levels of basic need satisfaction result in enhanced positive affective states, which in turn foster cognition by broadening cognitive processes (Stanley & Schutte, 2023). Specifically, it has been hypothesized that a combination of valence (i.e., activity pleasantness) and arousal (i.e., motivational intensity to approach or avoid certain stimuli) may have an impact on EFs (Kuhbandner & Zehetleitner, 2011).

Although there is consistent evidence supporting positive effects on cognition of chronic exercise with delivery styles in which educators generate engagement and positive affective states (Pesce et al., 2023), the influence of delivery style and related affective states on the relationship between acute cognitively challenging bouts and children's cognitive performance remains largely unexplored. To date, no studies manipulated delivery style characteristics and, to the best of our knowledge, only two studies considered the mediational role of affective states in the relation between acute cognitively challenging exercise and executive control (Bulten et al., 2022; Schmidt et al., 2016). However, findings remain inconclusive with valence mediating the effect of cognitive engagement on executive control in one study (Schmidt et al., 2016), but not in the other (Bulten et al., 2022).

Thus, the first aim of the study was to investigate the effect of different feedback forms (no feedback [NO-FB], standard acoustic environment [ST-FB], standard acoustic environment combined with positive feedback [PO-FB]) during an acute cognitively challenging bout of exergaming on children's (a) executive control (primary outcome); and (b) other attention network performances (i.e., alerting and orienting) and their interactive functioning (Fan et al., 2009). The second aim was to test whether affective states (valence and arousal) also differ between feedback forms. The third aim was to test whether valence and arousal mediate the effect of feedback on cognitive performance. Based on piecemeal evidence of enhanced positive affective states after positive feedback and after exposure to music (Bigliassi et al., 2018; Fransen et al., 2018; Fritz et al., 2013; Peifer et al., 2020), we hypothesized that feedback conditions would differentially impact affective states (PO-FB > ST-FB > NO-FB). Based on the overcompensation hypothesis of the self–control model (Audiffren & André, 2015), according to which cognitive resources are less depleted in presence of positive affective states, we hypothesized that feedback forms would differentially impact cognitive performance, mediated by affective states (PO-FB > ST-FB > NO-FB).

2. Methods

This study was part of the project "School–based physical activity and children's cognitive functioning: The quest for theory–driven interventions". The project aims to investigate the effects of qualitative and quantitative characteristics of designed school–based bouts of exercise on children's cognitive functions. The project was preregistered in the German Clinical Trials Registry (registration number: DRKS00023254). The cantonal ethics committee approved the study protocol (BASEC number: 2020–00624), which adhered to the latest Declaration of Helsinki.

2.1. Participants

One hundred eight children aged 10–13 years ($M = 11.0$, $SD = 0.8$; 48% female) were recruited, class–wise, from several primary schools in the region of Bern, Switzerland. To be eligible for the study, children had to be aged between 9 and 13 years old and without a diagnosed developmental disorder affecting cognition or motor function. Moreover, it was mandatory that legal guardians of all children provided written informed consent and that children agreed to participate. For feedback effects on the primary cognitive outcome (i.e., executive control), we conducted an a–priori power analysis using the SuperPower Shiny app. We defined a within–subjects design with three feedback conditions and estimated effects based on a previous acute study (Best, 2012) with alpha error probability = 0.05 and correlation between repeated measures $r = 0.40$. We assumed that children's executive control performance (as difference value, see section 2.5.) would be faster after PO-FB ($M = 100$ ms, $SD = 80$), compared to ST-FB ($M = 110$ ms, $SD = 80$) and NO-FB ($M = 120$ ms, $SD = 80$). To satisfy counterbalancing requirements, we tested the power of $N = 100$ participants. Using 2000 simulations, results showed a power of >80% for Bonferroni–adjusted pairwise comparisons among feedback conditions.

Of the 108 participants recruited, two were excluded due to injuries that occurred outside the study. Due to technical problems with the tablets used for attentional testing, there was some loss of data (1.1%). Since Little's MCAR test has led to a non–significant result ($p = 0.989$), the missing values were imputed using the expectation–maximization algorithm. Participants' background variables are presented in Table 1.

Table 1
Participants' background variables.

Background variables	*M* (*SD*)
Age (years)	11.0 (0.8)
Biological sex (% female)	49%
Socioeconomic status [2–14]	8.9 (2.1)
Body mass index (kg/m^2)	18.6 (3.0)
Pubertal developmental status [3–12]	4.9 (2.0)
Habitual physical activity [1–5]	2.6 (0.6)
VO_2max (ml/kg/min)	52.3 (6.6)
Weekly videogame time [min]	39.4 (63.9)
Need for cognition [19–95]	59.5 (10.7)
Need for affect [-30–30]	7.7 (7.5)

2.2. Design and procedures

In the current within–subjects crossover design study, acute bouts consisted in a specifically adapted exergame to ensure standardized manipulation of feedback in one of three conditions: NO-FB, ST-FB, or PO-FB. The study was conducted over a period of four weeks with random counterbalancing of experimental conditions. Specifically, we created six sequences (i.e., all permutations of the three experimental conditions) and randomly assigned each child to one sequence. During the first week, data was collected on two days. On the first day, background characteristics were assessed by a questionnaire including demographic, biological, developmental, physical, and cognitive factors. Subsequently, weight and height were assessed for BMI computation, and children performed the 20–m Shuttle Run test to assess their maximum heart rate (HR) and fitness level. Of this wide range of background variables, the following variables are those derived from the literature, which are commonly controlled for and reported as potentially influencing the acute exercise–cognition relation: Age, biological sex, BMI, socioeconomic status, pubertal developmental status, habitual physical activity (Herold et al., 2021; Ludyga et al., 2016; Pesce, 2009; Pesce et al., 2021). In addition, we assessed variables specifically tailored for the present acute exercise study with cognitively challenging exergaming and manipulation of the affect–inducing feedback form: Weekly videogame practice, need for cognition, and need for affect. Acceptable reliability and validity were demonstrated for background variables (for a detailed description and references see Appendix A). On the second day, children participated in a familiarization session: Each child completed a tutorial of the exergaming intervention that is described below. Subsequently, to familiarize children with attentional testing, they performed the practice block of the revised Attention Network Test (ANT–R; Fan et al., 2009).

Between the second and fourth week, children participated individually in one exergame session per week, which took place at the same time and day each week. Before [pre–test], during (every 5 min), and after exergaming [post–test], valence, arousal, physical exertion, cognitive engagement were collected; flow was assessed during (every 5 min), and after exergaming [post–test]. Variables were assessed in the following order: Valence and arousal, physical exertion, cognitive engagement, and flow. The multiple time points from baseline to post–exergaming allowed to test whether the manipulation was effective, as reflected in the alteration of subjective experiences (e.g., Benzing et al., 2016; Egger et al., 2018). These variables have acceptable reliability and validity (see Appendix A). HR was assessed every 3 s during exergaming to ensure that exercise intensity was kept constant. After each exergaming session, attentional testing was performed with ANT–R (Fan et al., 2009). The experimental protocol and timeline of weekly sessions are depicted in Fig. 1. Each session lasted about 34 min. While children were blinded to conditions, assessors were not.

2.3. Intervention and experimental conditions

Exergaming was used as intervention. It is an enjoyable, physically, and cognitively challenging form of exercise that integrates multimodal immediate feedback systems, ranging from visual animations to music and sound effects (Benzing & Schmidt, 2018; see Appendix B for a detailed explanation of the manipulation of physical and cognitive task demands of exergaming and the following video for exergaming task examples: https://vimeo.com/759054046). During exergaming, participants were immersed in an underwater game scenario and performed different movements (e.g., jumps, squats, punches; Martin–Niedecken et al., 2020). They wore motion–based trackers attached to their wrists and ankles as well as an HR sensor to constantly track their movements and HR. The high cognitive challenge (continuously adapted to the ongoing individual performance across five progressive difficulty levels) and the 15 min bout duration were chosen according to the results of previous studies (Anzeneder, Zehnder, Martin–Niedecken, et al., 2023;

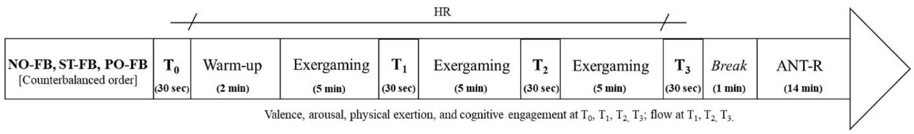


Fig. 1. Experimental protocol of weekly sessions.
Note. NO-FB: No feedback. ST-FB: Standard acoustic environment. PO-FB: Standard acoustic environment with positive feedback. T_0: Before exergaming, T_1: 5 min exergaming, T_2: 10 min exergaming, T_3: After exergaming. ANT–R: Revised Attention Network Test.

Anzeneder, Zehnder, Schmid, et al., 2023). The physical intensity was maintained at roughly 65% HR_{max} to (a) ensure comparability with most acute exercise–cognition studies (Pontifex et al., 2019); (b) align with evidence of cognitive benefits of moderate to vigorous intensities (Ludyga et al., 2016); and (c) avoid feelings of displeasure typical of vigorous exercise beyond the ventilatory threshold (Benjamin et al., 2012), due to the interplay of cognitive processes and affective responses to different exercise intensities (Ekkekakis, 2008).

Affective states were induced through different feedback forms. During NO-FB, children played the exergame without auditory signals and received only visual feedback integrated into the exergame, indicating the correctness and accuracy of their movements (e.g., stars lighting up for correct movements or gates turning red for incorrect ones), as well as the progression of difficulty levels (i.e., the background of the game scenario was colored differently according to the difficulty level). During ST-FB, visual feedback was accompanied by motivating music that increased in tempo with the difficulty level (i.e., faster tempo during more difficult levels), along with sound effects from the standard version of the exergame (e.g., virtual audience cheering and clapping hands in case of correct movements; see Appendix B). During PO-FB, children played the exergame in ST-FB, and researchers provided 15 standardized positive personal feedback every 5 min of activity. The feedback protocol included phrases such as “well done”, “great”, “very good”, or “keep it up” for correct movements and “no problem”, “go for it”, “you can do this”, or “try again” for incorrect movements.

2.4. Control and manipulation check variables

Several variables were assessed to test whether experimental manipulation had succeeded in eliciting physical exertion and cognitive engagement constantly during the exergaming bout (see Fig. 1). *HR* was assessed with PolarTeam2 belts and transmitters. *Perceived physical exertion* (RPE) and *cognitive engagement* (RCE) were assessed with Borg RPE and the adapted RCE scale, respectively.

Flow was assessed with the Core Flow Scale as a measure of immersion specific to the virtual reality environment. The rationale for including flow as a manipulation check variable was based on evidence that positive feedback enhances flow experience (Peifer et al., 2020), which, in turn, is linked to positive affective states (Huang et al., 2018). Indeed, external visual–auditory cues in a virtual environment may lessen reliance on cognitive effort to attenuate unpleasant interoceptive sensations associated with effortful exercise (Jones & Ekkekakis, 2019). Acceptable psychometric properties have been shown for all control and manipulation check variables (see Appendix A).

2.5. Cognitive performance

A child–adapted version of ANT–R (Fan et al., 2009) was used on Inquisit 5 to assess the efficiency of: (a) *executive control* (primary outcome), (b) *alerting* and *orienting performances*, as well as (c) the *interaction of executive control with alerting and orienting networks*. For the primary outcome, a retest reliability ranging from 0.61 to 0.71 has been shown (Macleod et al., 2010); it largely overlaps with that computed on the present dataset (ICC: 0.70 to 0.85). There are four cue conditions (no, double, valid spatial, invalid spatial) and two congruency conditions (central target arrow surrounded by congruent or incongruent flanker arrows). Children must identify the direction of the center arrow by pressing a right or left button while ignoring flanker arrows. Reaction times (RTs) and response accuracy are recorded. Each attention system performance is computed as a difference value of RTs and accuracy. For example, executive control (flanker effect) is calculated as [incongruent – congruent trials]. See Appendix C for a detailed description of ANT–R.

2.6. Affective states

Valence was assessed using the *Feeling Scale* (FS; Hardy & Rejeski, 1989). Children were asked to rate their present feelings on an 11–point bipolar single–item scale that ranges from −5 (very bad) to +5 (very good) along a displeasure–pleasure continuum. *Arousal* was assessed using the single–item pictorial Self–Assessment Manikin (SAM; Bradley & Lang, 1994). For both scales, acceptable psychometric properties have been provided with a convergent validity of $r = 0.67$ for valence (between FS and SAM valence subscales) and $r = 0.31$ for arousal (between SAM arousal subscale and Felt Arousal scale; Thorenz et al., 2024). In the present dataset, reliability was good for valence (ICC: 0.74 to 0.87) and acceptable for arousal (ICC: 0.65 to 0.82).

2.7. Statistical analyses

Analyses were performed using IBM SPSS version 27.0. Preliminary analyses were run using repeated measures ANOVAs for the comparison of control and manipulation check variables among feedback conditions over exergaming time. A further ANOVA was run to compare HR average among feedback conditions. An initial 3 (feedback conditions) × 4 (cue conditions) × 2 (flanker conditions) repeated measures ANOVA model was performed, separately for overall RTs and response accuracy, to test whether the classical cue–and flanker effects reported in the literature (Fan et al., 2009) could be replicated and were affected by feedback conditions.

For main analyses of the primary outcome, a repeated measures ANOVA model with feedback condition as factor was run separately for RT and accuracy differences, computed by subtracting flanker conditions pairwise in a theory–driven manner (see Appendix C). Subsequently, these difference values were used to contrast feedback effects using post–hoc Bonferroni–adjusted pairwise comparisons. For alerting and orienting performances and their interactions with executive control, analogous repeated measures ANOVA models were run separately for RT and accuracy differences, computed by subtracting cue conditions pairwise in a theory–driven manner (see Appendix C), followed by post–hoc Bonferroni–adjusted pairwise comparisons.

To test the effects of feedback on affective states over exergaming time and differences in affect at the different time points, a 3 (feedback conditions) × 4 (time points) repeated measures ANOVA model was performed separately for valence and arousal. Bonferroni–adjusted post–hoc pairwise comparisons were used to evaluate feedback × time effects. Subsequently, to test the effect of feedback on affective states, a repeated measures ANOVA model was performed with feedback as factor and, separately, with valence and arousal at post–test. We used post–test scores of affective states to ensure that intervention effects on mediating variables (affective states) and outcomes (cognitive performance) emerge from the same experimental design. However, we also satisfied temporal ordering assumptions (Stuart et al., 2021) by assessing post–exercise affective states before cognitive performance, necessarily separated by less than 2 min in an acute study designed to assesses short–term, transient effects.

In case of significant feedback effects of the main ANOVAs on cognitive performance, bivariate correlations were calculated to test the association of the cognitive performance of interest with post–test scores of affective states. Subsequently, bias–corrected bootstrap analyses (95% BC confidence interval) were calculated using SPSS MEMORE syntax to test potential mediations and reveal the indirect effects as significantly different from zero (Montoya & Hayes, 2017). In this multiple mediation model the independent variables were the pairwise contrasted feedback conditions that were found to be significant in the previous analyses. The mediating variables were post–test scores of valence and arousal. The dependent variables were cognitive performances that were significantly influenced by feedback. For each significant pairwise feedback comparison, we calculated difference values that reflect the mean tendency in the groups (Montoya & Hayes, 2017).

In an additional exploratory analysis, the potential influence of individual–level covariates was investigated using the same 3 × 4 × 2 repeated measures analysis model in a subsequent ANCOVA, including background variables as covariates (age, biological sex, BMI, pubertal developmental status, socioeconomic status, habitual physical activity, cardiovascular fitness, need for cognition, need for affect, weekly videogame practice). For all analyses, median RTs were used because of the non–normal distribution of RTs. All analyses were performed also on mean RTs, with and without the six multivariate outliers identified through Mahalanobis distance ($p < 0.001$); results show a similar pattern of effects. The significance level was set at $\alpha = 0.05$ for all analyses and η_p^2 was reported as effect size estimation (small effect size = 0.01, medium effect size = 0.06, large effect size = 0.14).

3. Results

3.1. Control and manipulation check variables

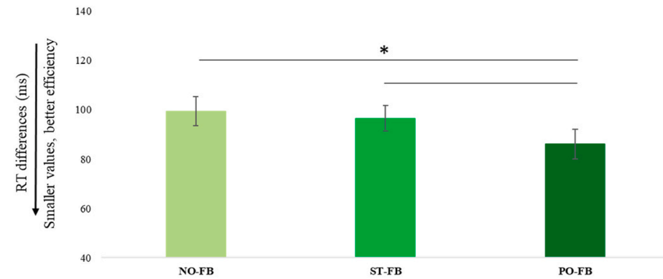
Descriptive statistics of control and manipulation check variables among time points are presented in Appendix D. For RPE and RCE a significant effect of time emerged (RPE: $p < 0.001$; $\eta_p^2 = 0.79$; RCE: $p < 0.001$; $\eta_p^2 = 0.68$). The intended similarity among conditions was also confirmed by objective HR data ($p = 0.164$, $\eta_p^2 = 0.04$). Concerning flow, significant effects of time ($p < 0.001$; $\eta_p^2 = 0.35$) and feedback condition emerged ($p < 0.001$; $\eta_p^2 = 0.29$). As concerns feedback effects of interest, flow experience was higher in PO-FB compared to the other conditions (PO-FB vs. NO-FB: $p < 0.001$, $\eta_p^2 = 0.21$; PO-FB vs. ST-FB: $p < 0.001$, $\eta_p^2 = 0.22$) with no further differences (ST-FB vs. NO-FB: $p = 0.257$, $\eta_p^2 = 0.03$).

3.2. Cognitive performance

A first ANOVA on overall RTs replicated the cue– (F [3, 97] = 357.23, $p < 0.001$, $\eta_p^2 = 0.92$), flanker– (F [1, 99] = 393.55, $p < 0.001$, $\eta_p^2 = 0.79$) and cue × flanker effects (F [3, 97] = 10.00, $p < 0.001$, $\eta_p^2 = 0.24$) reported in the literature (Fan et al., 2009).

Regarding main analyses of the primary outcome, a significant feedback condition effect on executive control RTs with medium effect size emerged (F [2, 98] = 4.58, $p = 0.013$, $\eta_p^2 = 0.09$; see Fig. 2). Post–hoc pairwise comparisons revealed faster RTs after PO-FB compared to NO-FB ($p = 0.023$, $\eta_p^2 = 0.07$) and ST-FB conditions ($p = 0.033$, $\eta_p^2 = 0.06$), whereas NO-FB and ST-FB did not differ from each other ($p = 1.000$, $\eta_p^2 = 0.04$). There were no feedback effects for accuracy ($p = 0.917$, $\eta_p^2 < 0.01$), indicating a lack of speed–accuracy trade–off effects.

No feedback effects emerged for RT and accuracy performances under cue conditions that reflect the efficiency of alerting or orienting networks (*RT*: $p = 0.206$, $\eta_p^2 = 0.08$; *accuracy*: $p = 0.716$, $\eta_p^2 = 0.04$). No effects of feedback emerged for the interaction of executive control with alerting and orienting (*RT*: $p = 0.778$, $\eta_p^2 = 0.03$; *accuracy*: $p = 0.124$, $\eta_p^2 = 0.09$). Further ANCOVAs revealed no significant interaction effects of feedback with individual characteristic ($ps > 0.05$, $\eta_{ps}^2 < 0.09$).



	NO-FB	ST-FB	PO-FB
Flanker effect	*M* (*SE*)	*M* (*SE*)	*M* (*SE*)
	99.47 (5.86)	96.55 (5.23)	86.18 (6.02)

Fig. 2. Feedback effects on executive control (flanker effect).
Note. NO-FB: No feedback. ST-FB: Standard acoustic environment. PO-FB: Standard acoustic environment with positive feedback. Flanker effect is computed as RT difference [incongruent – congruent trials]. Error bars represent the standard error of the mean. *Significant differences: PO-FB vs. NO-FB: $p = 0.023$, $\eta_p^2 = 0.07$; PO-FB vs. ST-FB: $p = 0.033$, $\eta_p^2 = 0.06$.

3.3. Affective states

A significant effect of time emerged for valence ($p < 0.001$, $\eta_p^2 = 0.24$) and arousal ($p < 0.001$, $\eta_p^2 = 0.61$). For valence only, a significant effect of feedback condition emerged ($p = 0.010$; $\eta_p^2 = 0.09$) with higher scores in PO-FB compared to the other conditions (PO-FB vs. NO-FB: $p = 0.011$, $\eta_p^2 = 0.08$; PO-FB vs. ST-FB: $p = 0.042$, $\eta_p^2 = 0.04$). For arousal only, a significant effect of time × feedback condition emerged ($p = 0.009$; $\eta_p^2 = 0.16$) with higher values in PO-FB compared to the other conditions (PO-FB vs. NO-FB: $p = 0.046$, $\eta_p^2 = 0.04$; PO-FB vs. ST-FB: $p = 0.047$, $\eta_p^2 = 0.04$). See Appendix D for a detailed description feedback condition and time × feedback condition effects on valence and arousal.

Moreover, a significant effect of feedback emerged on post–test scores of valence (F [2, 98] = 5.92, $p = 0.004$, $\eta_p^2 = 0.11$), but not arousal ($p = 0.425$, $\eta_p^2 = 0.02$; see Fig. 3). Pairwise comparisons showed that PO-FB was perceived as most pleasant (PO-FB vs. NO-FB: $p = 0.003$, $\eta_p^2 = 0.09$; PO-FB vs. ST-FB: $p = 0.004$, $\eta_p^2 = 0.08$) with no differences between ST-FB and NO-FB ($p = 0.538$, $\eta_p^2 = 0.00$; see Fig. 3)

3.4. Affective states and cognitive performance: correlations and mediations[2]

To investigate whether beneficial effects on executive control found after PO-FB were associated with affective states after PO-FB, executive control RTs (flanker effect) as well as RTs under incongruent and congruent flanker conditions were submitted to bivariate correlation with post–test scores of valence and arousal. Valence correlated with executive control RTs (flanker effect) as well as with RTs under both incongruent and congruent conditions. Arousal showed no significant correlations (see Table 2).

In addition, post–test scores of valence and arousal did not mediate feedback effects on executive control performance (see Fig. 4), and valence and arousal did not account for a different proportion of

[2] Due to the exploratory nature of mediation analyses (Bulten et al., 2022; Schmidt et al., 2016) and considering evidence of potential affective rebounding effects after cessation of exercise (Ekkekakis et al., 2011), correlations and mediations were also run with affective states' change scores (Post–Pre/Pre). Analyses show similar results: (a) valence only was associated with executive control RTs in PO-FB ($r = -0.21$, $p = 0.033$); (b) neither valence (PO-FB vs. NO-FB: 95% CI [–2.61, 6.46]; PO-FB vs. ST-FB: 95% CI [–0.41, 4.28]) nor arousal (PO-FB vs. NO-FB: 95% CI [–2.37, 4.16]; PO-FB vs. ST-FB: 95% CI [–2.78, 1.63]) mediated feedback effects on executive control.

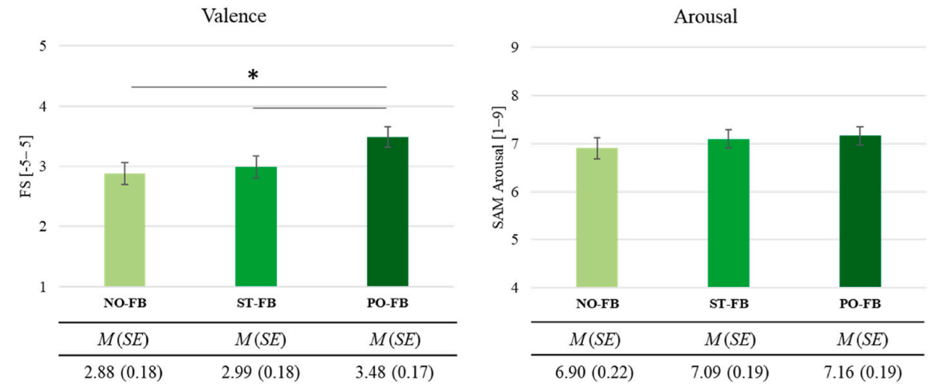


Fig. 3. Feedback effects on post–test scores of affective states.
Note. NO-FB: No feedback. ST-FB: Standard acoustic environment. PO-FB: Standard acoustic environment with positive feedback. Error bars represent the standard error of the mean. *Significant differences: PO-FB vs. NO-FB: $p = 0.003$, $\eta_p^2 = 0.09$; PO-FB vs. ST-FB: $p = 0.004$, $\eta_p^2 = 0.08$.

Table 2
Correlation coefficients among executive control performance and post–test scores of affective states in each feedback condition.

Affective states	Executive control RTs	RTs incongruent	RTs congruent
PO-FB:			
Valence	**$r = -0.23$, $p =$ 0.029**	**$r = -0.20$, $p =$ 0.042**	**$r = -0.26$, $p =$ 0.008**
Arousal	$r = -0.05$, $p =$ 0.655	$r = -0.14$, $p =$ 0.155	$r = -0.14$, $p =$ 0.165
ST-FB:			
Valence	$r = -0.04$, $p =$ 0.684	$r = -0.02$, $p =$ 0.813	$r = -0.01$, $p =$ 0.915
Arousal	$r = -0.09$, $p =$ 0.403	$r = -0.17$, $p =$ 0.100	$r = -0.17$, $p =$ 0.084
NO-FB:			
Valence	$r = -0.03$, $p =$ 0.748	$r = -0.01$, $p =$ 0.949	$r = 0.01$, $p = 0.939$
Arousal	$r = -0.05$, $p =$ 0.650	$r = -0.05$, $p =$ 0.629	$r = -0.04$, $p =$ 0.697

Note. NO-FB: No feedback. ST-FB: Standard acoustic environment. PO-FB: Standard acoustic environment with positive feedback. RTs: Reaction times. Executive control is calculated as [incongruent – congruent trials]. Significant results bolded.

variance (see Table 3).

4. Discussion

The present study aimed to extend to acute exercise–cognition research a novel interest in the role of contextual factors that recently emerged in the field of chronic exercise studies in relation to cognitive (Pesce et al., 2023) and, more broadly, mental health outcomes (Vella, Aidman, et al., 2023; Vella, Sutcliffe, et al., 2023). Within the broader construct of contextual factors, we focused on the delivery style as a key aspect influencing affective states (Pesce et al., 2023). Specifically, we evaluated the effect of different feedback forms during an acute cognitively challenging exergaming on children's cognitive performance. Moreover, we examined whether feedback forms influence affective states, and whether affective states induced by the exercise bout mediate feedback effects on cognitive performance. Results suggest that positive feedback benefited children's executive control and enhanced affective states most. Conversely, the efficiency of alerting, orienting, and their interaction with executive control was unaffected by feedback forms. Among affective states, only valence elicited by positive feedback was associated with the subsequent executive control performance; however, neither valence nor arousal mediated feedback effects on executive control.

As concerns the first research aim (i.e., feedback effects on cognitive performance), results suggest that delivery styles such as positive feedback matter: In line with our hypothesis, executive control seems to benefit most when children receive positive feedback. Given that under this feedback condition, children were faster in conflict resolution while maintaining a high response accuracy, these effects were likely not due to a speed–accuracy trade–off. However, feedback forms seem not to

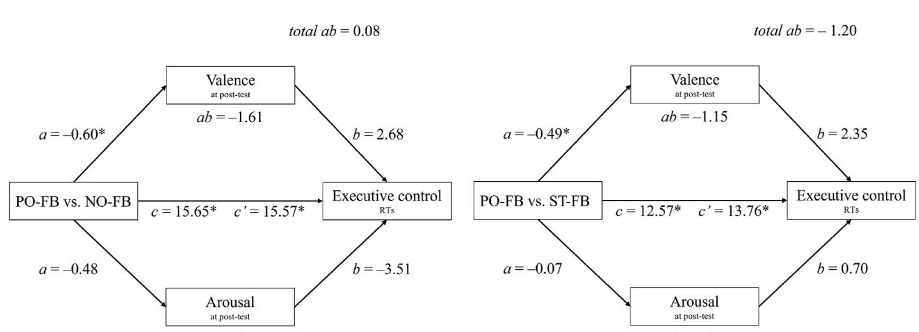


Fig. 4. Mediation model with feedback comparisons as predictors, affective states as mediators, and executive control RTs as outcome variable
Note. NO-FB: No feedback. ST-FB: Standard acoustic environment. PO-FB: Standard acoustic environment with positive feedback. RTs: Reaction times. Paths a, b, c, and c': Estimates of fixed effects. Path ab: Indirect effect.
*$p < 0.05$.

Table 3
Mediation model with feedback comparisons as predictors, affective states as mediators, and executive control RTs as outcome variable (point estimates, standard errors, and 95% bias-corrected bootstrap confidence intervals).

Panel A. PO-FB vs. NO-FB			
Path	*M*	*SE*	*(LLCI, ULCI)*
Path c	15.65[a]	5.75	4.24, 27.05
Path c'	15.57[a]	6.14	3.37, 27.77
Path a (valence)	−0.60[a]	0.19	−0.99, −0.21
Path a (arousal)	−0.48	0.21	−0.89, −0.07
Path b (valence)	2.68	3.21	−3.70, 9.06
Path b (arousal)	−3.51	3.01	−9.49, 2.47
Path ab (valence)	−1.61	1.92	−6.08, 1.72
Path ab (arousal)	1.68	1.91	−1.37, 6.09
Pairwise contrasts between indirect effects of valence and arousal	−3.29	2.92	−9.99, 1.57
Path ab total	0.08	2.47	−5.25, 4.68
Panel B. PO-FB vs. ST-FB			
Path	*M*	*SE*	*(LLCI, ULCI)*
Path c	12.57[a]	4.84	2.95, 22.18
Path c'	13.76[a]	5.10	3.64, 23.89
Path a (valence)	−0.49[a]	0.17	−0.82, −0.16
Path a (arousal)	−0.07	0.14	−0.36, 0.22
Path b (valence)	2.35	3.06	−3.73, 8.42
Path b (arousal)	0.70	3.46	−6.17, 7.58
Path ab (valence)	−1.15	1.35	−4.07, 1.39
Path ab (arousal)	−0.05	0.47	−1.15, 0.83
Pairwise contrasts between indirect effects of valence and arousal	−1.10	1.48	−4.26, 1.79
Path ab total	−1.20	1.37	−4.02, 1.32

Note. NO-FB: No feedback. ST-FB: Standard acoustic environment. PO-FB: Standard acoustic environment with positive feedback. Paths a, b, and c': Estimates of fixed effects. Path ab: indirect effect.
[a] $p < 0.05$.

differentially influence children's alerting, orienting, or their interaction with executive control. Speculatively, the fact that only executive control but not the other attention networks were susceptible to acute exergame–based bouts might be interpreted according to evidence of selectively larger exercise effects on tasks that require greater inhibitory control, as in the case of incongruent task conditions (Lubans et al., 2022). The absence of effects on alerting and orienting performances is in line with available evidence that neither a routine aerobic exercise (van den Berg et al., 2018) nor a cognitively challenging exergaming (Anzeneder, Zehnder, Martin–Niedecken, et al., 2023; Anzeneder, Zehnder, Schmid, et al., 2023) seems to influence these networks and might depend on ANT–R indices reliability: The higher within–subject variance found for alerting and orienting compared to executive control indices suggests that in the context of within–subjects designs, the first probably have lower statistical power than the latter (MacLeod et al., 2010). Moreover, feedback effects on cognitive performance were not moderated by any individual characteristic; future studies powered to consider this wide range of covariates are needed to confirm the generalizability of results to preadolescent children, independently of interindividual differences in biological, developmental, physical, and cognitive factors.

As concerns the second aim (i.e., feedback effects on affective states), results suggest that positive feedback provided from researchers during exergaming enhances valence more than the sole immersion in the exergame with or without music. A possible explanation for the personal feedback effects is that encouraging, supportive feedback provided by researchers fulfills basic psychological needs (Ryan & Deci, 2000) and reinforces children's perceived competence, thus enhancing affective states (Fransen et al., 2018). This supposition is confirmed by the flow experience being higher in the positive feedback compared to the other conditions. In fact, positive feedback may enhance the likelihood of flow because it reinforces individuals' feeling of confidence in task completion (Peifer et al., 2020). Speculatively, in the absence of direct measures of neurophysiological indices, this explanation aligns with evidence that both immersion and flow experiences in a virtual reality environment are reflected in a reduced activation of areas of the prefrontal cortex. Virtual reality cues may shift the attentional focus away from internal body signals and reduce cognitive control over the affective responses to them, as reflected in the reduced activation in the right dorsolateral prefrontal cortex (Jones & Ekkekakis, 2019). In addition, positive feedback that enhances flow experience may reduce self–referential processing, as reflected in a decreased activation of the medial prefrontal cortex (Ulrich et al., 2014).

The absence of differential effects between only visual and visual––acoustic feedback conditions (i.e., no feedback and standard acoustic environment, respectively) on affective states was unexpected, as it didn't support synchronization and distraction theories (Bigliassi et al., 2018; Fritz et al., 2013). In fact, children perceived the standard acoustic environment as equally flow–eliciting as the no feedback form. A possible explanation refers to the unique exergaming environment. This environment, rich in visual animation and immersive elements (Martin–Niedecken et al., 2020), has been shown to induce positive affective responses by shifting attention from interoceptive to visual–acoustic exteroceptive stimuli (Jones & Ekkekakis, 2019). This immersion may have captured children's attention to a point that adding music and sound effects as in the standard acoustic environment condition was not effective in further enhancing the experience of presence (Cummings & Bailenson, 2016).

More interestingly, beyond the individual effects of feedback on cognitive performance and affective states, the third aim was to investigate whether affective states explain the effect of feedback on cognitive performance. Our study provides suggestive evidence that after positive feedback valence is weakly associated with executive control performance, but it does not mediate feedback effects on executive control. The association between valence and executive control partially aligns with the overcompensation hypothesis of the self–control model and the dopaminergic hypothesis (Audiffren & André, 2015), according to which, positive feedback may have generated an optimal affective state to improve EFs. However, the absence of a mediation of valence and arousal does not support the hypothesis that an affective mechanism may underlie the transient benefits on executive control of a cognitively challenging exergaming coupled with positive feedback. Since exergaming is highly motivating and immersive, future studies may want to contrast the mediating role of valence and arousal in bouts of exercise with a different delivery mode (e.g., face-to-face).

The potential of exercise to boost EF performance while inducing positive affect has been highlighted in recent evidence synthesis of chronic exercise studies (Pesce et al., 2023), suggesting that delivery styles that challenge EFs, while also eliciting emotional investment, may maximize exercise benefits on cognition. However, in acute exercise and cognition research with children, most studies did not consider affective states at all (e.g., Budde et al., 2008; Egger et al., 2018; Flynn & Richert, 2018), merely used them as potential covariates (e.g., Anzeneder, Zehnder, Martin–Niedecken, et al., 2023; Anzeneder, Zehnder, Schmid, et al., 2023; Bedard et al., 2021; Benzing et al., 2016), or tested a potential mediation of valence only but led to inconsistent conclusions (Bulten et al., 2022; Schmidt et al., 2016). Schmidt et al. (2016) found evidence for mediation, whereas Bulten et al. (2022) did not, suggesting that the absence of mediation might be due to a ceiling effect in affective responses to the experimental manipulation. Our study, instead, did not exhibit this limitation, since manipulation check variables, along with affective states and the executive control performance of interest, seemed to be differentially sensitive to the positive feedback condition compared to the other feedback forms. Nevertheless, our results cannot support the notion that affective states are psychological mechanisms underlying the transient effect of a cognitively challenging bout of exercise on children's executive control. Thus, our lack of mediation does not support the assumptions of the macro–theory of positive functioning, suggesting that delivery styles that encourage competence can effectively enhance affective states that, in turn, broaden cognitive functioning, leading to more efficient conflict resolution (Stanley & Schutte, 2023). Moreover, the fact that valence and arousal did not account for a different proportion of variance misaligns with previous evidence of independent effects of these affective states on executive control (Kuhbandner & Zehetleitner, 2011). Future research should increasingly consider the interplay between valence and arousal and disentangle their impact on cognitive performance.

This study has limitations that should be noted. First, the choice of the study design was influenced by the need to set priorities between main manipulations to address the first study aim and time availability in the ecological school setting. Since the first aim of the study was not to examine acute exergame effects on executive control, but rather to identify the effect of different feedback forms on it, we did not include a sedentary control group or a pre–test assessment of cognitive performance. Thus, we could neither disentangle exercise and feedback effects, nor exclude the influence of day–to–day variability on cognitive performance. However, to minimize the influence of day–to–day variability, we rigorously matched all testing conditions across participants and scheduled exergaming sessions and attentional testing always at the same day and time for each child. Future studies should additionally include a sedentary control group and incorporate a within–subjects, crossover pre–posttest comparison (Pontifex et al., 2019) to allow to control, in mediation analyses, for mediator–outcome confounders such as baseline performances (Stuart et al., 2021; Vo et al., 2020). Second, we did not include a fourth experimental condition of feedback provided by an avatar integrated into the exergame that would have allowed to disentangle the added positive value of the personal, human factor from the positive feedback content, which remains an issue for future research. Third, the absence of physiological and neuroimaging measures of affective states and of cognitive processes constrains the proposed interpretations in terms of underlying mechanisms that combine neuroscience and psychological perspectives (Chang, 2016; Wilson et al., 2020). Fourth, to better understand the nuanced pattern of feedback effects on children's cognition, further research should include additional measures of individual characteristics, such as perceived competence, which might have been influenced by feedback (Fransen et al., 2018) and could potentially account for the observed feedback effects on cognition. Lastly, our sample size was powered for the main analyses on the primary outcome; the additional exploratory analysis considering background characteristics as covariates may have been underpowered to detect their influence and ensure generalizability to children differing in those characteristics.

5. Conclusions and practical implications

Results suggest that combining cognitively challenging exergaming with supportive, encouraging feedback benefit children's executive control more than exergaming without positive feedback. The mechanisms driving such effects likely go beyond the mere enhancement of affective states. Speculatively, it might be that positive feedback and encouragement, combined with the provision of individually adapted cognitive and physical challenges, also supported children's perceived competence (Fransen et al., 2018).

Some characteristics of exergaming, such as the feeling of immersion, the simultaneous integration of physical and cognitive challenges, and positive feedback that have been proven efficacious in the present study might also be transferred into traditional physical activity or sport games without virtual reality. The feeling of immersion, unique to virtual reality, may also be generated to some extent in educational settings for young children by coupling storytelling and physical activity, whose additive effects have been investigated in chronic physical activity research (Duncan et al., 2019; Mavilidi et al., 2023). For school children, both in physical education and during active breaks in the classroom, traditional physical activity games may be altered to generate a progression of complexity similar to that of exergaming, while eliciting imaginative immersion in different environments (e.g., traditional games adapted to imaginative environments as sky and undersea with incremental demands on inhibition; Tomporowski et al., 2015). The outcomes of this study might also inform the development and refinement of cognitive demands to be embedded into enriched sports activity programs (e.g., Alesi et al., 2020). Lastly, since positive feedback during exergaming resulted in cognitive benefits and affective enhancement, the above manipulations of exercise task complexity in educational and sports contexts could be coupled with positive feedback which, beyond its motivating role (Fransen et al., 2018; Mouratidis et al., 2008), may allow to reap largest cognitive benefits. In conclusion, the results of the study, though obtained through the specific delivery mode of exergaming, provide evidence that contributes to embedding the acute exercise–cognition relation into a broader framework of research and application that encompasses cognitive and affective dimensions of exercise task characteristics and contextual factors.

Funding

This study was supported by the Swiss National Science Foundation (Eccellenza grant number: 181074).

Ethical approval

Ethical approval was granted by the respective cantonal ethics committees (BASEC 2020-00624) and the trial was registered at ClinicalTrials.gov (DRKS00023254).

CRediT authorship contribution statement

Sofia Anzeneder: Writing – review & editing, Writing – original draft, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Jürg Schmid:** Writing – review & editing, Methodology. **Cäcilia Zehnder:** Writing – review & editing, Methodology. **Lairan Koch:** Writing – review & editing, Data curation. **Anna Lisa Martin-Niedecken:** Writing – review & editing, Conceptualization. **Mirko Schmidt:** Writing – review & editing, Writing – original draft, Supervision, Funding acquisition, Conceptualization. **Valentin Benzing:** Writing – review & editing, Supervision, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Mirko Schmidt received financial support from the Swiss National Science Foundation.

Data availability

Data will be made available on request.

Acknowledgments

We would like to thank the participating teachers, parents, and children, as well as the students who helped collect data.

Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.mhpa.2024.100621.

References

Alesi, M., Giordano, G., Giaccone, M., Basile, M., Costa, S., & Bianco, A. (2020). Effects of the enriched sports activities-program on executive functions in Italian children. *Journal of Functional Morphology and Kinesiology, 23*(5), 26. https://doi.org/10.3390/jfmk5020026

Anzeneder, S., Zehnder, C., Martin–Niedecken, A. L., Schmidt, M., & Benzing, V. (2023). Acute exercise and children's cognitive functioning: What is the optimal dose of cognitive challenge? *Psychology of Sport and Exercise, 66*, Article 102404. https://doi.org/10.1016/j.psychsport.2023.102404

Anzeneder, S., Zehnder, C., Schmid, J., Martin–Niedecken, A. L., Schmidt, M., & Benzing, V. (2023). Dose–response relation between the duration of a cognitively challenging bout of physical exercise and children's cognition. *Scandinavian Journal of Medicine & Science in Sports, 33*(8), 1439–1451. https://doi.org/10.1111/sms.14370

Audiffren, M., & André, N. (2015). The strength model of self–control revisited: Linking acute and chronic effects of exercise on executive functions. *Journal of Sport and Health Science, 4*(1), 30–46. https://doi.org/10.1016/j.jshs.2014.09.002

Audiffren, M., Tomporowski, P. D., & Zagrodnik, J. (2009). Acute aerobic exercise and information processing: Modulation of executive control in a random number generation task. *Acta Psychologica, 132*(1), 85–95. https://doi.org/10.1016/j.actpsy.2009.06.008

Basso, J. C., & Suzuki, W. A. (2017). The effects of acute exercise on mood, cognition, neurophysiology, and neurochemical pathways: A review. *Brain Plasticity, 2*(2), 127–152. https://doi.org/10.3233/BPL–160040

Becker, L., Büchel, D., Lehmann, T., Kehne, M., & Baumeister, J. (2023). Mobile electro–encephalography reveals differences in cortical processing during exercises with lower and higher cognitive demands in preadolescent children. *Pediatric Exercise Science, 35*(4), 214–224. https://doi.org/10.1123/pes.2021–0212

Bedard, C., Bremer, E., Graham, J. D., Chirico, D., & Cairney, J. (2021). Examining the effects of acute cognitively engaging physical activity on cognition in children. *Frontiers in Psychology, 12*, Article 653133. https://doi.org/10.3389/fpsyg.2021.653133

Benjamin, C. C., Rowlands, A., & Parfitt, G. (2012). Pattering of affective responses during a graded exercise test in children and adolescents. *Pediatric Exercise Science, 24*(2), 275–288. https://doi.org/10.1123/pes.24.2.275

Benzing, V., Heinks, T., Eggenberger, N., & Schmidt, M. (2016). Acute cognitively engaging exergame—based physical activity enhances executive functions in adolescents. *PLoS One, 11*(12), Article e0167501. https://doi.org/10.1371/journal.pone.0167501

Benzing, V., & Schmidt, M. (2018). Exergaming for children and adolescents: Strengths, weaknesses, opportunities and threats. *Journal of Clinical Medicine, 7*(11), 422. https://doi.org/10.3390/jcm7110422

Bernardo, P. D., Bains, A., Westwood, S., & Mograbi, D. C. (2021). Mood induction using virtual reality: A systematic review of recent findings. *Journal of Technology in Behavioral Science, 6*, 3–24. https://doi.org/10.1007/s41347-020-00152-9

Best, J. R. (2012). Exergaming immediately enhances children's executive function. *Developmental Psychology, 48*(5), 1501–1510. https://doi.org/10.1037/a0026648

Bigliassi, M., Karageorghis, C. I., Bishop, D. T., Nowicky, A. V., & Wright, M. J. (2018). Cerebral effects of music during isometric exercise: An fMRI study. *International Journal of Psychophysiology, 133*, 131–139. https://doi.org/10.1016/j.ijpsycho.2018.07.475

Bradley, M. M., & Lang, P. J. (1994). Measuring emotion: The self–assessment Manikin and the semantic differential. *Journal of Behavior Therapy and Experimental Psychiatry, 25*(1), 49–59. https://doi.org/10.1016/0005–7916(94)90063–9

Budde, H., Voelcker–Rehage, C., Pietraßyk–Kendziorra, S., Ribeiro, P., & Tidow, G. (2008). Acute coordinative exercise improves attentional performance in adolescents. *Neuroscience Letters, 441*(2), 219–223. https://doi.org/10.1016/j.neulet.2008.06.024

Bulten, R., Bedard, C., Graham, J. D., & Cairney, J. (2022). Effect of cognitively engaging physical activity on executive functions in children. *Frontiers in Psychology, 13*, Article 841192. https://doi.org/10.3389/fpsyg.2022.841192

Chang, Y. K. (2016). Acute exercise and event–related potential: Current status and future prospects. In T. McMorris (Ed.), *Exercise–cognition interaction: Neuroscience perspectives* (pp. 105–130). Elsevier Academic Press.

Cummings, J. J., & Bailenson, J. N. (2016). How immersive is enough? A meta–analysis of the effect of immersive technology on user presence. *Media Psychology, 19*(2), 272–309. https://doi.org/10.1080/15213269.2015.1015740

De Greeff, J. W., Bosker, R., Oosterlaan, J., Visscher, C., & Hartman, E. (2018). Effects of physical activity on executive functions, attention and academic performance in preadolescent children: A meta–analysis. *Journal of Science and Medicine in Sport, 21*(5), 501–507. https://doi.org/10.1016/j.jsams.2017.09.595

Diamond, A. (2013). Executive functions. *Annual Review of Psychology, 64*, 135–168. https://doi.org/10.1146/annurev–psych–113011–143750

Duncan, M., Cunningham, A., & Eyre, E. (2019). A combined movement and storytelling intervention enhances motor competence and language ability in preschoolers to a greater extent than movement or storytelling alone. *European Physical Education Review, 25*(1), 221–235. https://doi.org/10.1177/1356336X17715772

Egger, F., Conzelmann, A., & Schmidt, M. (2018). The effect of acute cognitively engaging physical activity breaks on children's executive functions: Too much of a good thing? *Psychology of Sport and Exercise, 36*, 178–186. https://doi.org/10.1016/j.psychsport.2018.02.014

Ekkekakis, P. (2008). The study of affective responses to acute exercise: The Dual–Mode Model. In R. Stelter, & K. K. Roessler (Eds.), *New approaches to sport and exercise psychology* (pp. 119–146). Meyer & Meyer Sport.

Ekkekakis, P., Parfitt, G., & Petruzzello, S. J. (2011). The pleasure and displeasure people feel when they exercise at different intensities. *Sports Medicine, 41*, 641–671. https://doi.org/10.2165/11590680-000000000-00000

Fan, J., Gu, X., Guise, K. G., Liu, X., Fossella, J., Wang, H., & Posner, M. I. (2009). Testing the behavioral interaction and integration of attentional networks. *Brain and Cognition, 70*(2), 209–220. https://doi.org/10.1016/j.bandc.2009.02.002

Flynn, R. M., & Richert, R. A. (2018). Cognitive, not physical, engagement in video gaming influences executive functioning. *Journal of Cognition and Development, 19*(1), 1–20. https://doi.org/10.1080/15248372.2017.1419246

Fransen, K., Boen, F., Vansteenkiste, M., Mertens, N., & Vande Broek, G. (2018). The power of competence support: The impact of coaches and athlete leaders on intrinsic motivation and performance. *Scandinavian Journal of Medicine & Science in Sports, 28*(2), 725–745. https://doi.org/10.1111/sms.12950

Fredrickson, B. L. (2004). The broaden–and–build theory of positive emotions. *Philosophical Transactions of the Royal Society of London, 359*(1449), 1367–1378. https://doi.org/10.1098/rstb.2004.1512

Fritz, T. H., Hardikar, S., Demoucron, M., Niessen, M., Demey, M., Giot, O., Li, Y., Haynes, J. D., Villringer, A., & Leman, M. (2013). Musical agency reduces perceived exertion during strenuous physical performance. *Proceedings of the National Academy of Sciences of the United States of America, 110*(44), 17784–17789. https://doi.org/10.1073/pnas.1217252110x

Furley, P., Schütz, L. M., & Wood, G. (2023). A critical review of research on executive functions in sport and exercise. *International Review of Sport and Exercise Psychology*, 1–29. https://doi.org/10.1080/1750984X.2023.2217437

Hardy, C. J., & Rejeski, W. J. (1989). Not what, but how one feels: The measurement of affect during exercise. *Journal of Sport & Exercise Psychology, 11*, 304–317. https://doi.org/10.1123/jsep.11.3.304

Herold, F., Hamacher, D., Schega, L., & Müller, N. G. (2018). Thinking while moving or moving while thinking - concepts of motor-cognitive training for cognitive performance enhancement. *Frontiers in Aging Neuroscience, 10*, 228. https://doi.org/10.3389/fnagi.2018.00228

Herold, F., Törpel, A., Hamacher, D., Budde, H., Zou, L., Strobach, T., Müller, N. G., & Gronwald, T. (2021). Causes and consequences of interindividual response variability: A call to apply a more rigorous research design in acute exercise–cognition studies. *Frontiers in Physiology, 12*, Article 682891. https://doi.org/10.3389/fphys.2021.682891

Huang, H. C., Pham, T. T., Wong, M. K., Chiu, H. Y., Yang, Y. H., & Teng, C. I. (2018). How to create flow experience in exergames? *Perspective of Flow Theory, Telematics and Informatics, 35*(5), 1288–1296. https://doi.org/10.1016/j.tele.2018.03.001

Jones, L., & Ekkekakis, P. (2019). Affect and prefrontal hemodynamics during exercise under immersive audiovisual stimulation: Improving the experience of exercise for overweight adults. *Journal of Sport and Health Science, 8*(4), 325–338. https://doi.org/10.1016/j.jshs.2019.03.003

Kuhbandner, C., & Zehetleitner, M. (2011). Dissociable effects of valence and arousal in adaptive executive control. *PLoS One, 6*(12), Article e29287. https://doi.org/10.1371/journal.pone.0029287

Liew, J. (2012). Effortful control, executive functions, and education: Bringing self—regulatory and social emotional competencies to the table. *Child Development Perspectives, 6*(2), 105–111. https://doi.org/10.1111/j.1750–8606.2011.00196.x

Lubans, D. R., Leahy, A. A., Mavilidi, M. F., & Valkenborghs, S. R. (2022). Physical Activity, fitness, and executive functions in youth: Effects, moderators, and mechanisms. *Current Topics in Behavioral Neurosciences, 53*, 103–130. https://doi.org/10.1007/7854_2021_271

Ludyga, S., Gerber, M., Brand, S., Holsboer–Trachsler, E., & Puhse, U. (2016). Acute effects of moderate aerobic exercise on specific aspects of executive function in different age and fitness groups: A meta–analysis. *Psychophysiology, 53*(11), 1611–1626. https://doi.org/10.1111/psyp.12736

Macleod, J. W., Lawrence, M. A., McConnell, M. M., Eskes, G. A., Klein, R. M., & Shore, D. I. (2010). Appraising the ANT: Psychometric and theoretical considerations of the attention network test. *Neuropsychology, 24*(5), 637–651. https://doi.org/10.1037/a0019803

Martin–Niedecken, A. L., Mahrer, A., Rogers, K., de Bruin, E. D., & Schättin, A. (2020). "HIIT" the ExerCube: Comparing the effectiveness of functional high–intensity interval training in conventional vs. exergame–based training. *Frontiers of Computer Science, 2*. https://doi.org/10.3389/fcomp.2020.00033. article 33.

Mavilidi, M. F., Pesce, C., Mazzoli, E., Bennett, S., Paas, F., Okely, A. D., & Howard, S. J. (2023). Effects of cognitively engaging physical activity on preschool children's cognitive outcomes. *Research Quarterly for Exercise & Sport, 94*(3), 839–852. https://doi.org/10.1080/02701367.2022.2059435

Montoya, A. K., & Hayes, A. F. (2017). Two–condition within–participant statistical mediation analysis: A path–analytic framework. *Psychological Methods, 22*(1), 6–27. https://doi.org/10.1037/met0000086

Mouratidis, A., Vansteenkiste, M., Lens, W., & Sideridis, G. (2008). The motivating role of positive feedback in sport and physical education: Evidence for a motivational model. *Journal of Sport & Exercise Psychology, 30*(2), 240–268. https://doi.org/10.1123/jsep.30.2.240

Paschen, L., Lehmann, T., Kehne, M., & Baumeister, J. (2019). Effects of acute physical exercise with low and high cognitive demands on executive functions in children: A systematic review. *Pediatric Exercise Science, 31*(3), 267–281. https://doi.org/10.1123/pes.2018–0215

Peifer, C., Schönfeld, P., Wolters, G., Aust, F., & Margraf, J. (2020). Well done! Effects of positive feedback on perceived self–efficacy, flow and performance in a mental arithmetic task. *Frontiers in Psychology, 11*, 1008. https://doi.org/10.3389/fpsyg.2020.01008

Pesce, C. (2009). An integrated approach to the effect of acute and chronic exercise on cognition: The linked role of individual and task constraints. In T. McMorris,

P. D. Tomporowski, & M. Audiffren (Eds.), *Exercise and cognitive function*. Wiley–Heinrich.

Pesce, C. (2012). Shifting the focus from quantitative to qualitative exercise characteristics in exercise and cognition research. *Journal of Sport & Exercise Psychology, 34*(6), 766–786. https://doi.org/10.1123/jsep.34.6.766

Pesce, C., Ballester, R., & Benzing, V. (2021). Giving physical activity and cognition research 'some soul': Focus on children and adolescents. *European Journal of Human Movement, 47*, 1–7. https://doi.org/10.21134/eurjhm.2021.47.1

Pesce, C., Vazou, S., Benzing, V., Álvarez–Bueno, C., Anzeneder, S., Mavilidi, M. F., Leone, L., & Schmidt, M. (2023). Effects of chronic physical activity on cognition across the lifespan: A systematic meta–review of randomized controlled trials and realist synthesis of contextualized mechanisms. *International Review of Sport and Exercise Psychology, 16*(1), 722–760. https://doi.org/10.1080/1750984X.2021.1929404

Petruzzello, S. J., Greene, D. R., Chizewski, A., Rougeau, K. M., & Greenlee, T. A. (2018). Acute vs. chronic effects of exercise on mental health. In H. Budde, & M. Wegner (Eds.), *The exercise effect on mental health* (pp. 442–476). CRC Press.

Pontifex, M. B., McGowan, A. L., Chandler, M. C., Gwizdala, K. L., Parks, A. C., Fenn, K., & Kamijo, K. (2019). A primer on investigating the after effects of acute bouts of physical activity on cognition. *Psychology of Sport and Exercise, 40*, 1–22. https://doi.org/10.1016/j.psychsport.2018.08.015

Ryan, R. M., & Deci, E. L. (2000). Intrinsic and extrinsic motivations: Classic definitions and new directions. *Contemporary Educational Psychology, 25*(1), 54–67. https://doi.org/10.1006/ceps.1999.1020

Schmidt, M., Benzing, V., & Kamer, M. (2016). Classroom–based physical activity breaks and children's attention: Cognitive engagement works. *Frontiers in Psychology, 7*, 1474. https://doi.org/10.3389/fpsyg.2016.01474

Schmidt, M., Egger, F., Anzeneder, S., & Benzing, V. (2021). Acute cognitively challenging physical activity to promote children's cognition. In R. Bailey (Ed.), *ICSSPE perspectives. Physical activity and sport during the first ten years of life: Multidisciplinary perspectives* (pp. 141–155). Routledge.

Serrien, D. J., Ivry, R. B., & Swinnen, S. P. (2007). The missing link between action and cognition. *Progress in Neurobiology, 82*(2), 95–107. https://doi.org/10.1016/j.pneurobio.2007.02.003

Stanley, P. J., & Schutte, N. S. (2023). Merging the self–determination theory and the broaden and build theory through the nexus of positive affect: A macro theory of positive functioning. *New Ideas in Psychology, 68*, Article 100979. https://doi.org/10.1016/j.newideapsych.2022.100979

Stojan, R., & Voelcker–Rehage, C. (2019). A systematic review on the cognitive benefits and neurophysiological correlates of exergaming in healthy older adults. *Journal of Clinical Medicine, 8*(5), 734. https://doi.org/10.3390/jcm8050734

Stuart, E. A., Schmid, I., Nguyen, T., Sarker, E., Pittman, A., Benke, K., Rudolph, K., et al. (2021). Assumptions not often assessed or satisfied in published mediation analyses in psychology and psychiatry. *Epidemiologic Reviews, 43*(1), 48–52. https://doi.org/10.1093/epirev/mxab007

Terry, P. C., Karageorghis, C. I., Curran, M. L., Martin, O. V., & Parsons–Smith, R. L. (2020). Effects of music in exercise and sport: A meta–analytic review. *Psychological Bulletin, 146*(2), 91–117. https://doi.org/10.1037/bul0000216

Thorenz, K., Sudeck, G., Berwinkel, A., & Weigelt, M. (2024). The affective responses to moderate physical activity: A further study to prove the convergent and the discriminant validity for the German versions of the feeling scale and the felt arousal scale. *Behavioral Sciences, 14*, 317. https://doi.org/10.3390/bs14040317

Tomporowski, P., McCullick, B., & Pesce, C. (2015). *Enhancing children's cognition with physical activity games*. Human Kinetics.

Ulrich, M., Keller, J., Hoenig, K., Waller, C., & Grön, G. (2014). Neural correlates of experimentally induced flow experiences. *NeuroImage, 86*, 194–202. https://doi.org/10.1016/j.neuroimage.2013.08.019

Van den Berg, V., Saliasi, E., Jolles, J., de Groot, R. H. M., Chinapaw, M. J. M., & Singh, A. S. (2018). Exercise of varying durations: No acute effects on cognitive performance in adolescents. *Frontiers in Neuroscience, 12*, 672, 0.3389/fnins.2018.00672.

Vella, S. A., Aidman, E., Teychenne, M., Smith, J. J., Swann, C., Rosenbaum, S., White, R. L., & Lubans, D. R. (2023). Optimizing the effects of physical activity on mental health and wellbeing: A joint consensus statement from sports medicine Australia and the Australian psychological society. *Journal of Science and Medicine in Sport/Sports Medicine Australia, 26*(2), 132–139. https://doi.org/10.1016/j.jsams.2023.01.001

Vella, S. A., Sutcliffe, J. T., Fernandez, D., Liddelow, C., Aidman, E., Teychenne, M., Smith, J. J., Swann, C., Rosenbaum, S., White, R. L., & Lubans, D. R. (2023). Context matters: A review of reviews examining the effects of contextual factors in physical activity interventions on mental health and wellbeing. *Mental Health and Physical Activity, 25*, Article 100520. https://doi.org/10.1016/j.mhpa.2023.100520

Verburgh, L., Königs, M., Scherder, E. J. A., & Oosterlaan, J. (2014). Physical exercise and executive functions in preadolescent children, adolescents and young adults: A meta–analysis. *British Journal of Sports Medicine, 48*(12), 973–979. https://doi.org/10.1136/bjsports–2012–091441

Vo, T. T., Superchi, C., Boutron, I., & Vansteelandt, S. (2020). The conduct and reporting of mediation analysis in recently published randomized controlled trials: Results from a methodological systematic review. *Journal of Clinical Epidemiology, 117*, 78–88. https://doi.org/10.1016/j.jclinepi.2019.10.001

Wilson, K. A., James, G. A., Kiltis, C. D., & Bush, K. A. (2020). Combining physiological and neuroimaging measures to predict affect processing induced by affectively valent image stimuli. *Scientific Reports, 10*, 9298. https://doi.org/10.1038/s41598–020–66109–3

Appendix A. Description of background, control and manipulation check variables

Background variables

Beside *age, biological sex* and *writing hand*, the *body weight* and *height* were measured according to standardized protocols with children wearing regular clothes without shoes. *Body Mass Index* (BMI) was calculated [weight (kg)/ height (m)^2]. *Socioeconomic status* was assessed using the Family Affluence Scale III (Torsheim et al., 2016). This consists of six questions about the family (e.g., whether they have their own bedroom or number of family–owned computers). The response format varies by item and points are given for a higher number, for example of computers. The prosperity index is then calculated as the sum of the points on the six items. Acceptable reliability and validity have been demonstrated (Torsheim et al., 2016). *Pubertal developmental status* was assessed using the German version of the pubertal developmental scale (Watzlawik, 2009). This consists of three questions for each sex, asking for example: "Have you noticed a deepening of your voice?". Responses are given on a 4–point Likert scale, scoring 1–4 points (e.g., not yet started; barely started; definitely started; seems complete). The puberty index (3–12 points) is calculated by summing up the scores of the three items. Acceptable reliability and validity have been demonstrated (Watzlawik, 2009). The *habitual physical activity* was assessed using the German version of the physical activity questionnaire for older children (Crocker et al., 1997). This 7–day recall instrument consists of 10 items, asking to indicate which physical activity children have performed (item 1), how physically active they were during school hours (items 2–8), and how often they performed a moderate to vigorous physical activity (item 9). The response format varies by item and points are given for a higher number, for example of performed activities. The summary score (1–5 points) is calculated by the mean of items 1–9. Item 10 can be used to identify children who had unusual activity during the previous week. The questionnaire is a valid and reliable measure of children's physical activity levels (Crocker et al., 1997). *Need for cognition*, defined as disposition to engage in and enjoy effortful cognitive activities (Preckel, 2014), was assessed using the German teen version of the Need for Cognition scale (Preckel, 2014). This consists of 19 questions, asking for example: "I would rather do something that requires little thought than something that is sure to challenge my thinking abilities". Responses are given on a 5–point Likert scale, scoring 1–5 points (from extremely uncharacteristic of me to extremely characteristic of me). Some items are reverse scored. The total score (19–95 points) is calculated by summing up the scores of the 19 items. Acceptable reliability and validity have been demonstrated (Preckel, 2014). *Need for affect*, described as the tendency to approach or avoid emotion–inducing situations and activities, was assessed using the short scale of the need for affect questionnaire (Appel et al., 2012). This consists of 10 questions, asking for example: "It is important for me to know how others are feeling". Responses are given on a 7–point Likert scale, scoring from –3 to +3 points (from extremely uncharacteristic of me to extremely characteristic of me). Some items are reverse scored. The total score (–30–30 points) is calculated by summing up the scores of the 10 items. Acceptable reliability and validity have been demonstrated (Apple et al., 2012). *Weekly videogame practice* was assessed, asking children to indicate how long they played videogames during the last 7 days (in minutes). This questionnaire was self–developed for the purposes of the current study and has not been validated yet. *Cardiovascular fitness (Vo^2max)* and HR_{max} were assessed by a 20–m Shuttle Run test (Léger et al., 1988). All participants wore a Polar H7 HR monitor that was connected to the Polar Team App (Polar Electro Oy, Finland), in which HR data was stored. The test was performed during a regular physical education lesson, under supervision of a physical education teacher. All children were familiar with this test and were encouraged by their teacher and the research team to exert maximum performance. The test had an initial running speed of 8.0 km/h that progressively increased with 0.5 km/h in one–minute stages. The highest completed stage with an accuracy of half a stage was recorded.

Control and manipulation check variables

Perceived physical exertion (RPE) was measured using the Borg RPE scale. Acceptable reliability and validity in preadolescents have been provided for this scale (Lamb, 1996). To determine children's *cognitive engagement* during exergaming, Borg RPE scale was adapted to ask for perceived cognitive engagement (RCE). Children had to answer the question: "How exhausting was the previous activity for your brain?". This adapted version is not a validated instrument but proved to be feasible with children and adolescents and sensitive to detect changes among intervention conditions (Benzing et al., 2016; Egger et al., 2018; Schmidt et al., 2016). In the present dataset reliability was acceptable for both physical exertion (ICC: 0.63 to 0.74) and cognitive engagement (ICC: 0.65 to 0.80). *HR* was assessed with PolarTeam2 belts and transmitters.

Flow experience was assessed using the Core Flow Scale (Martin & Jackson, 2008). This consists of 10 items, stating for example: "I am totally involved". Responses are rated on a 5–point Likert scale, ranging from "1" (strongly disagree) to "5" (strongly agree). The total score (1–5 points) is calculated by summing up the scores of the 10 items and then dividing them by 10. Acceptable reliability and validity have been demonstrated for the scale (Martin & Jackson, 2008). In the present dataset a high reliability was found for flow (ICC: 0.70 to 0.86).

References

Appel, M., Gnambs, T., & Maio, G.R. (2012). A short measure of the Need for Affect. *Journal of Personality Assessment*, *94*(4), 418–26. doi:10.1080/00223891.2012.666921.

Crocker, P.R.E., Bailey, D.A., Faulkner, R.A., Kowalski, K.C., & McGrath, R. (1997). Measuring general levels of physical activity: Preliminary evidence for the physical activity questionnaire for older children. *Medicine & Science in Sports & Exercise*, *29*(10), 1344–9. doi:10.1097/00005768–199710000–00011.

Lamb, K.L. (1996). Exercise regulation during cycle ergometry using the children's effort rating table (CERT) and rating of perceived exertion (RPE) scales. *Pediatric Exercise Science*, *8*(4), 337–50. doi:10.1123/pes.8.4.337.

Léger, L.A., Mercier, D., Gadoury, C., & Lambert, J. (1988). The multistage 20–meter shuttle run test for aerobic fitness. *Journal of Sports Sciences*, *6*, 93–101. doi:10.1080/02640418808729800.

Martin, A.J., & Jackson, S.A. (2008). Brief approaches to assessing task absorption and enhanced subjective experience: Examining 'short' and 'core' flow in diverse performance domains. *Motivation and Emotion*, *32*, 141–57. doi:10.1007/s11031–008–9094–0.

Preckel, F. (2014). Assessing need for cognition in early adolescence. *European Journal of Psychological Assessment*, *30*(1), 65–72. doi:10.1027/1015–5759/a000170.

Torsheim, T., Cavallo, F., Levin, K.A., Schnohr, C., Mazur, J., Niclasen, B., & Currie, C. (2016). Psychometric validation of the revised family affluence scale: A latent variable approach. *Child Indicators Research, 9*(3), 771–84. doi:10.1007/s12187–015–9339–x.

Watzlawik, M. (2009). Die Erfassung des Pubertätsstatus anhand der Pubertal Development Scale. *Diagnostica*, *55*(1), 55–65. doi:10.1026/0012–1924.55.1.55.

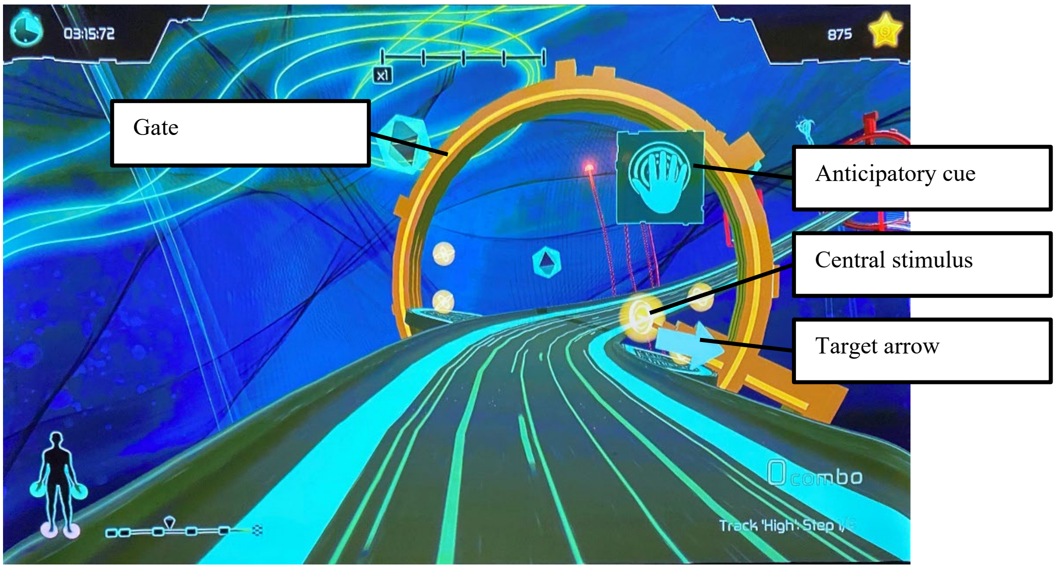
Appendix B. Exergaming tasks

ExerCube game setup:

We used a modified version of the exergame Sphery Racer (Martin-Niedecken et al., 2020), where physical and cognitive task demands were continuously adapted to children's ongoing performance. Children performed various functional workout movements (e.g., jumps, squats, punches or catching sideway points), while being immersed in a rapid underwater race game scenario. In this game scenario, they navigated an avatar through various colored gates. Each gate provided information regarding specific movements and cognitive tasks. Jumps, squats, skipping, and deep lunges (50% of total movements) were used to maintain the heart rate (HR) constant at approximately 65% HRmax. Punches and catching sideway points (50% of total movements) were used to manipulate the cognitive challenge. The latter, cognitively more challenging, movements were designed to mirror the attentional allocation processes involved in the ANT-R paradigm, including anticipatory cues that alerted and oriented attention (i.e., invalid cues ranging between 13%–19%) and targets that required interference control (i.e., incongruent rotation of the central stimulus ranging between 40% and 60%). The task difficulty, which ranged across five progressive levels, was continuously adjusted to children's ongoing performance: It became easier or more challenging if children made more or fewer than three errors within a 30 second period, respectively.

A video of exergaming tasks can be found here: https://vimeo.com/759054046

Step-by-step analysis of a catching point task example:



1. An anticipatory cue appears, potentially indicating the direction for the subsequent movement. *Note*: Cues can appear on the right (as in this example), left or on both sides of the gate. A valid cue indicates the correct movement direction (as in this example). An invalid cue is distracting, as it indicates the wrong movement direction. A double cue provides no spatial information.

2. When the gate comes closer, children must perform a specific movement based on the gate's color. *Note*: Yellow gates: Lateral shuffle steps while catching a target point (as in this example). Blue gates: Punches. Red gates: Jumps or squats. Violet gates: Skipping or deep lunges.

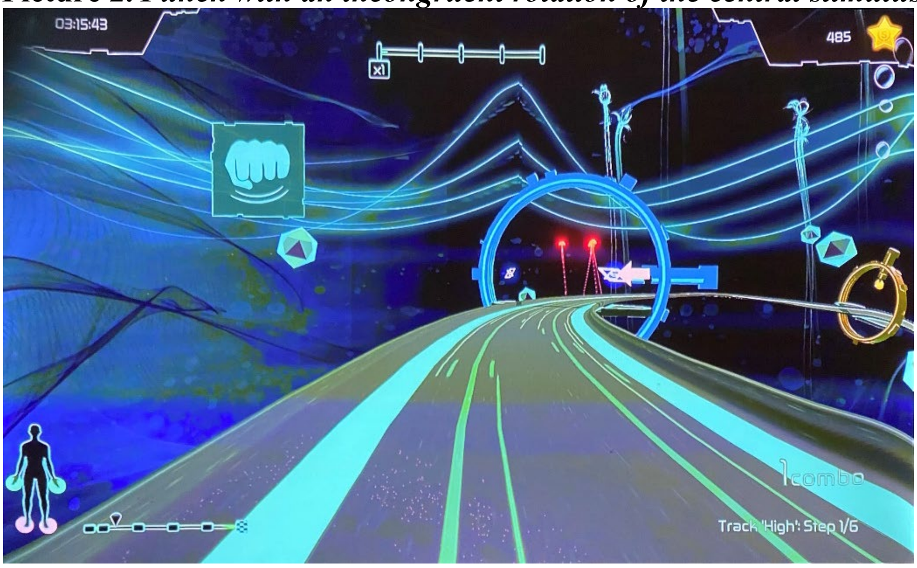
3. Movements must be performed following the direction of the target arrow, while ignoring the rotation of the central stimulus. *Note*: The direction of the target arrow as well as the rotation of the central stimulus can be right or left. The rotation of the central stimulus can be congruent (as in this example) or incongruent with the arrow direction. An incongruent rotation of the central stimulus is distracting.

Examples of movements used to manipulate the cognitive challenge:

Picture 1. ***Punch with a congruent rotation of the central stimulus but double cue***

Children must follow the direction of the target arrow (pointing here to the left), while ignoring the rotation of the congruent central stimulus (here a quadrangle on the left side). The double cue is not spatially informative (fists on both sides).

Picture 2. ***Punch with an incongruent rotation of the central stimulus but valid cue***



Children must follow the direction of the target arrow (pointing here to the left), while ignoring the rotation of the incongruent central stimulus (here a quadrangle on the right side). The cue is valid (fist on the left side).

Picture 3. ***Catching point with a congruent rotation of the central stimulus but invalid cue***

Children must follow the direction of the target arrow (pointing here to the right), while ignoring the rotation of the congruent central stimulus (here a circle on the right side). The cue is invalid (hand on the left side).

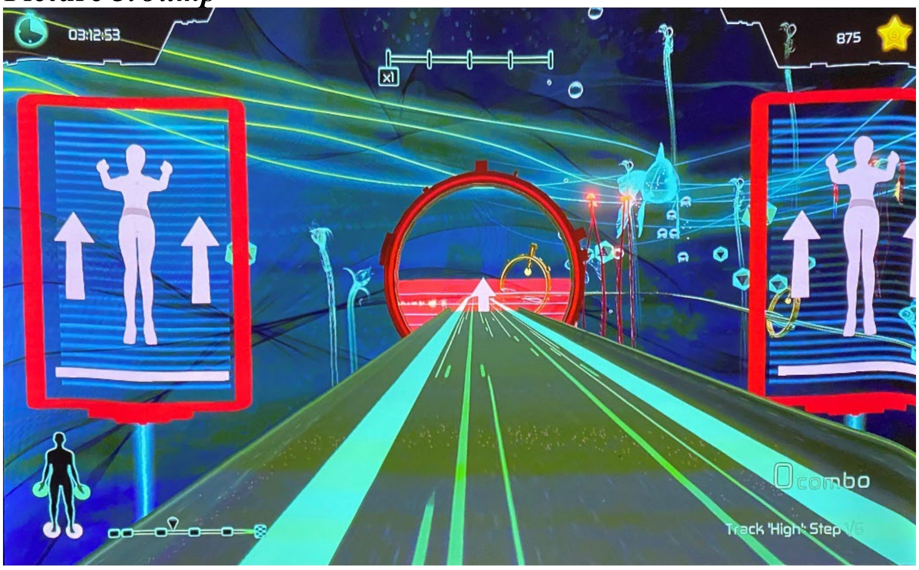
Picture 4. ***Catching point with an incongruent rotation of the central stimulus but valid cue***

Children must follow the direction of the target arrow (pointing here to the right), while ignoring the rotation of the incongruent central stimulus (here a circle on the left side). The cue is valid (hand on the right side).

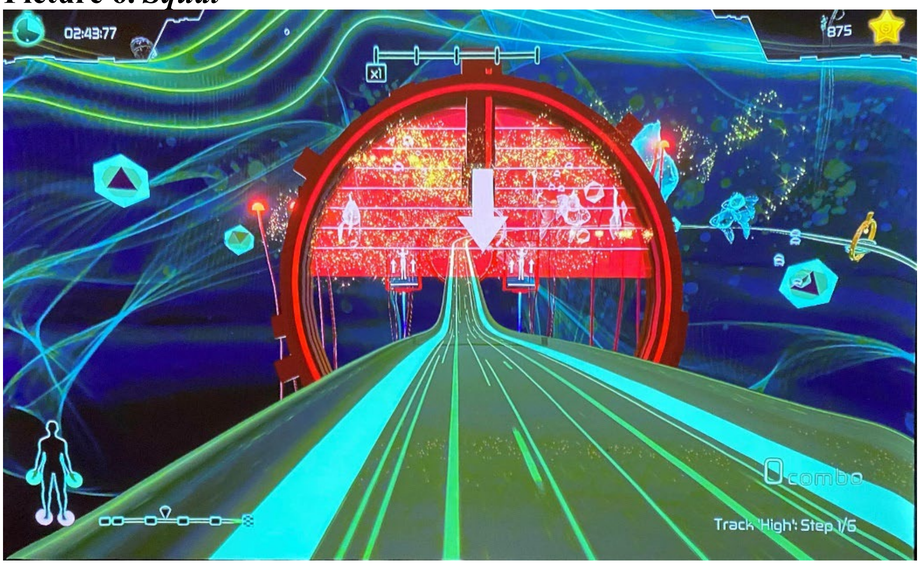
Examples of movements used to maintain children's heart rate constant

Picture 4. ***Skipping***

Picture 5. ***Jump***



Picture 6. ***Squat***



Appendix C. ANT-R

To capture the functioning of attention network systems, the ANT-R combines the attention cueing paradigm, which assesses alerting and orienting, and the flanker task, which assesses executive control. There are four cue conditions: no cue, double cue, valid spatial cue, and invalid spatial cue; and two congruency conditions: a central target arrow surrounded by congruent (>> > > > or < < < < <) or incongruent (>> < > > or < < > < <) lateral flanker arrows. Each trial begins with a central fixation cross, followed by no cue, a double cue informing that a target will occur soon, or a single spatial cue informing on the probable location of the upcoming target. A valid spatial cue indicates the location where a subsequent target will appear. An invalid spatial cue indicates the opposite location. Subsequently, a congruent or incongruent flanker condition appears. Children's task is to identify the direction of the center arrow by pressing a right or left button while ignoring the lateral flanker arrows. Reaction times (RTs) and response accuracy are recorded.

The task comprises two blocks of 72 trials (each bock with 12 no cue, 12 double cue, 36 valid spatial, and 12 invalid spatial trials) and lasts 14 min, including a 1-min break between the blocks. Responses with RTs faster than 200 ms or longer than 1700 ms were excluded automatically by the program. Further details on the task parameters and cue-target interval timing can be found elsewhere (Fan et al., 2009).

Each attention system performance is computed as a difference value of RTs and accuracy.

- *Executive control* (flanker effect) is calculated as [incongruent – congruent trials]. A smaller value for the RT difference and a smaller negative value for the accuracy difference reflect a better efficiency, because children can better inhibit the interference of incongruent flankers.

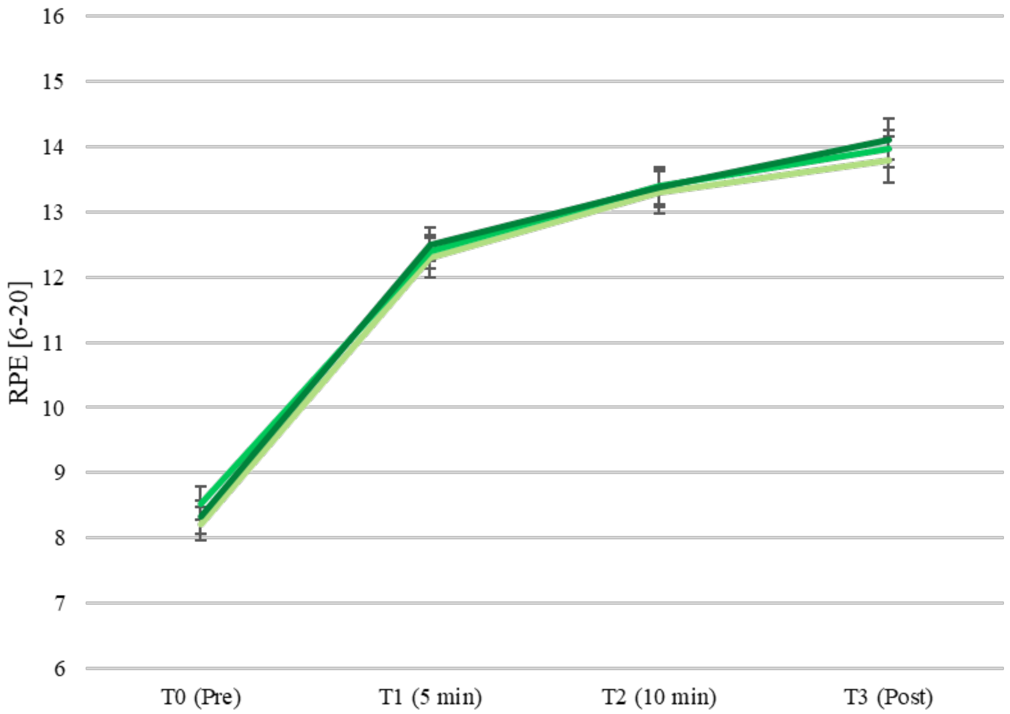
- *Alerting* is calculated as [no cue – double cue trials]. A larger value for the RT difference and a larger negative value for the accuracy difference reflect the benefit in speed/accuracy elicited by an alerting cue.
- *Orienting* involves engaging attention at a validly cued location [double cue – valid spatial cue trials] and disengaging attention from an invalidly cued location [invalid spatial cue – double cue trials]. A larger RT difference and a larger negative value for the accuracy difference reflect the benefit in speed/accuracy elicited by a valid spatial cue, and/or the cost elicited by an invalid spatial cue.

The interactive function of the three attention networks is assessed as the effect of alerting or orienting on executive control (flanker effect). It is measured as the difference of flanker effect under different cue conditions.

- The *effect of alerting on executive control* is calculated as [(no cue trials with incongruent flanker – no cue trials with congruent flanker) – (double cue trials with incongruent flanker – double cue trials with congruent flanker)]. A negative value indicates a negative impact of alerting on executive control.
- The *effect of orienting on executive control* is composed of the effects of *engaging* and *disengaging* attention on executive control. The effect of *engaging* is calculated as [(double cue trials with incongruent flanker – double cue trials with congruent flanker) – (spatial valid cue trials with incongruent flanker – spatial valid cue trials with congruent flanker)]. The effect of *disengaging* is calculated as [(spatial invalid cue trials with incongruent flanker – spatial invalid cue trials with congruent flanker) – (double cue trials with incongruent flanker – double cue trials with congruent flanker)]. For *engaging*, a positive value indicates the beneficial effect of validly oriented attention on executive control. Instead, for *disengaging*, a positive value indicates the cost of invalidly oriented attention.

Appendix D. Statistics of perceived physical exertion and cognitive engagement, HR, flow, valence, and arousal among feedback conditions and time points

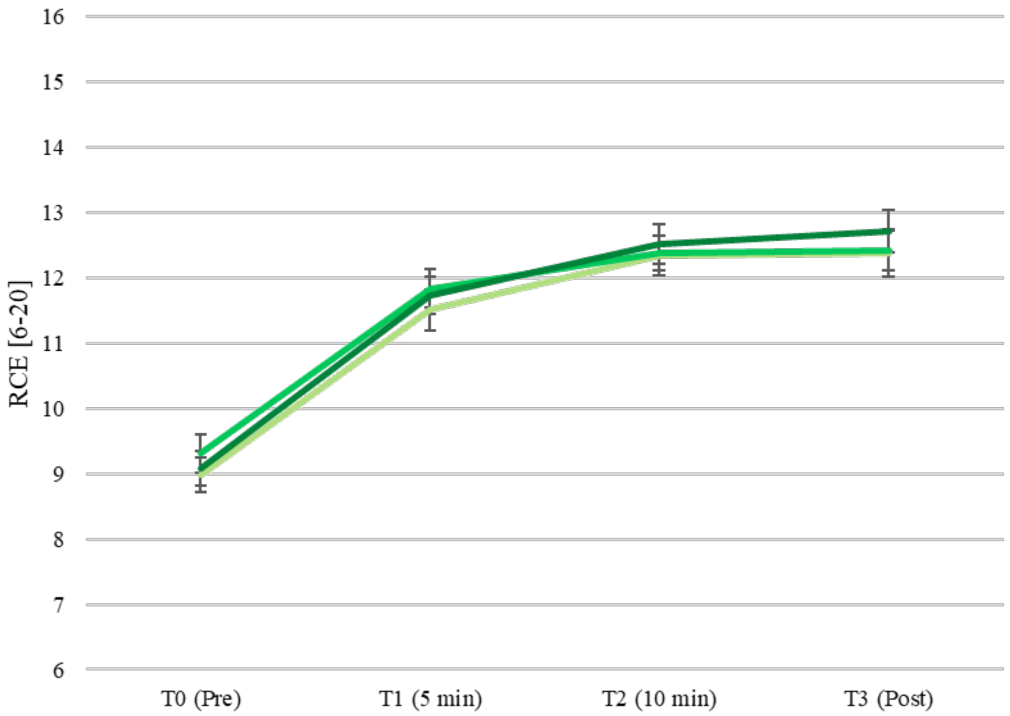
D1. Perceived physical exertion



	T0 (Pre)	T1 (5 min)	T2 (10 min)	T3 (Post)
	M (*SE*)	*M* (*SE*)	*M* (*SE*)	*M* (*SE*)
NO-FB	8.22 (0.25)	12.30 (0.29)	13.30 (0.33)	13.80 (0.36)
ST-FB	8.53 (0.26)	12.39 (0.26)	13.39 (0.27)	13.97 (0.29)
PO-FB	8.32 (0.25)	12.50 (0.26)	13.38 (0.30)	14.11 (0.32)

Note. NO-FB: No feedback. ST-FB: Standard acoustic environment. PO-FB: Standard acoustic environment and positive feedback. RPE: Rating of perceived exertion. Error bars represent the standard error of the mean. Effect of time: $p < 0.001$; $\eta^2_p = 0.79$. Effect of feedback condition: $p = 0.974$; $\eta^2_p = 0.001$. Effect of time × feedback condition: $p = 0.288$; $\eta^2_p = 0.07$.

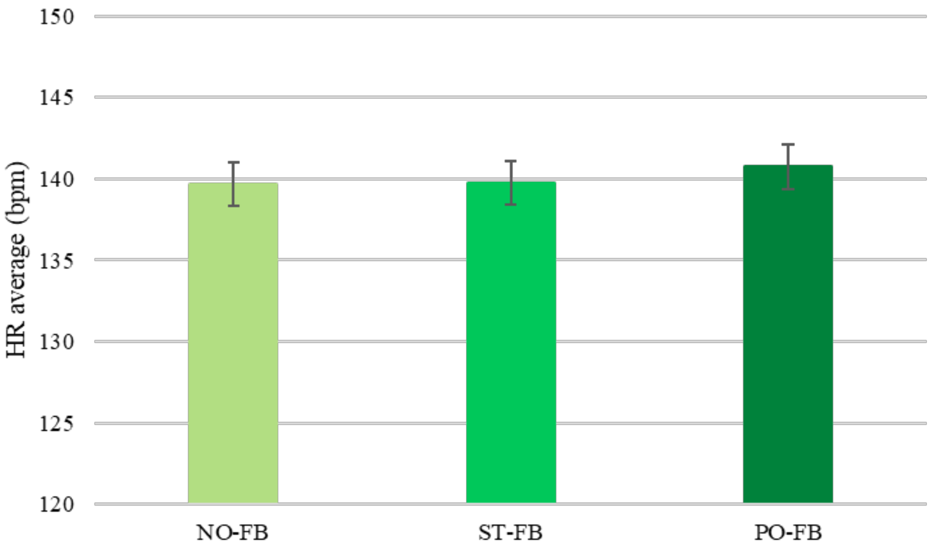
D2. Perceived cognitive engagement



	M (*SE*)	*M* (*SE*)	*M* (*SE*)	*M* (*SE*)
NO-FB	8.89 (0.26)	11.51 (0.31)	12.35 (0.30)	12.38 (0.36)
ST-FB	9.31 (0.29)	11.84 (0.29)	12.38 (0.26)	12.42 (0.31)
PO-FB	9.08 (0.27)	11.73 (0.28)	12.52 (0.31)	12.71 (0.32)

Note. NO-FB: No feedback. ST-FB: Standard acoustic environment. PO-FB: Standard acoustic environment and positive feedback. RCE: Rating of cognitive engagement. Error bars represent the standard error of the mean. Effect of time: $p < 0.001$; $\eta^2_p = 0.68$. Effect of feedback condition: $p = 0.203$; $\eta^2_p = 0.03$. Effect of time × feedback condition: $p = 0.494$; $\eta^2_p = 0.06$.

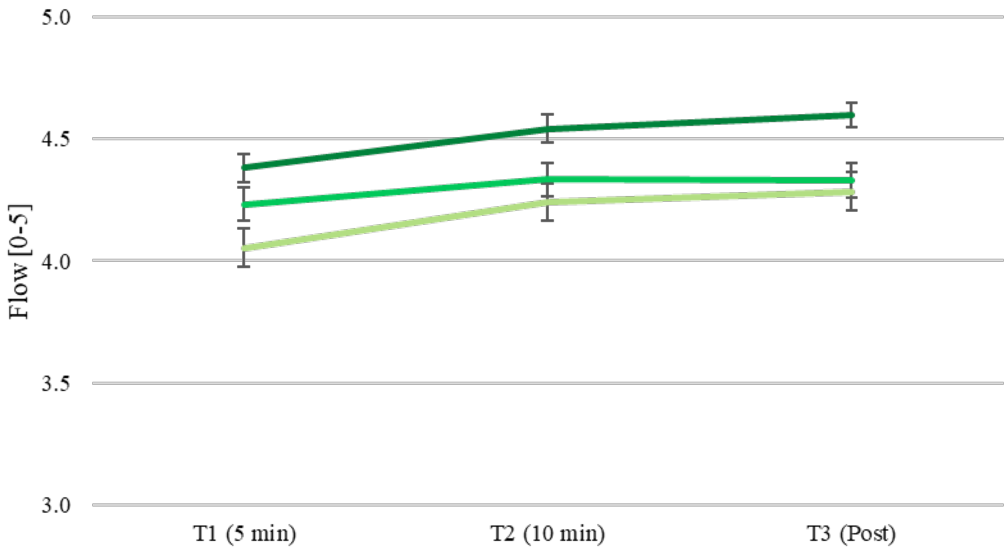
D3. HR average over exergaming time



M (*SE*)	*M* (*SE*)	*M* (*SE*)
139.67 (1.32)	139.76 (1.35)	140.74 (1.36)

Note. NO-FB: No feedback. ST-FB: Standard acoustic environment. PO-FB: Standard acoustic environment and positive feedback. Error bars represent the standard error of the mean. Effect of feedback condition: $p = 0.164$, $\eta^2_p = 0.04$.

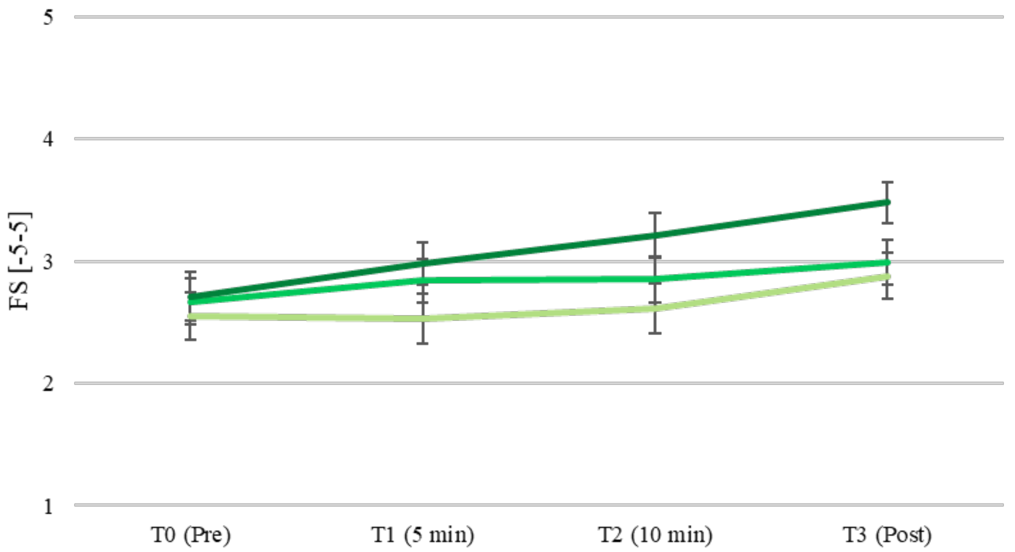
D4. Flow



	M (*SE*)	*M* (*SE*)	*M* (*SE*)
NO-FB	4.05 (0.08)	4.24 (0.08)	4.29 (0.08)
ST-FB	4.23 (0.07)	4.33 (0.07)	4.33 (0.07)
PO-FB	4.38 (0.06)	4.54 (0.06)	4.60 (0.05)

Note. *Note*. NO-FB: No feedback. ST-FB: Standard acoustic environment. PO-FB: Standard acoustic environment and positive feedback. Error bars represent the standard error of the mean. Effect of time: $p < 0.001$; $\eta^2_p = 0.35$. Effect of feedback condition: $p < 0.001$; $\eta^2_p = 0.29$. Effect of time × feedback condition: $p = 0.140$; $\eta^2_p = 0.07$. Results of post-hoc comparisons for feedback effect (significant results bolded): **PO-FB vs. NO-FB: $p < 0.001$, $\eta^2_p = 0.21$**; **PO-FB vs. ST-FB: $p < 0.001$, $\eta^2_p = 0.22$**; NO-FB vs. ST-FB: $p = 0.257$, $\eta^2_p = 0.03$.

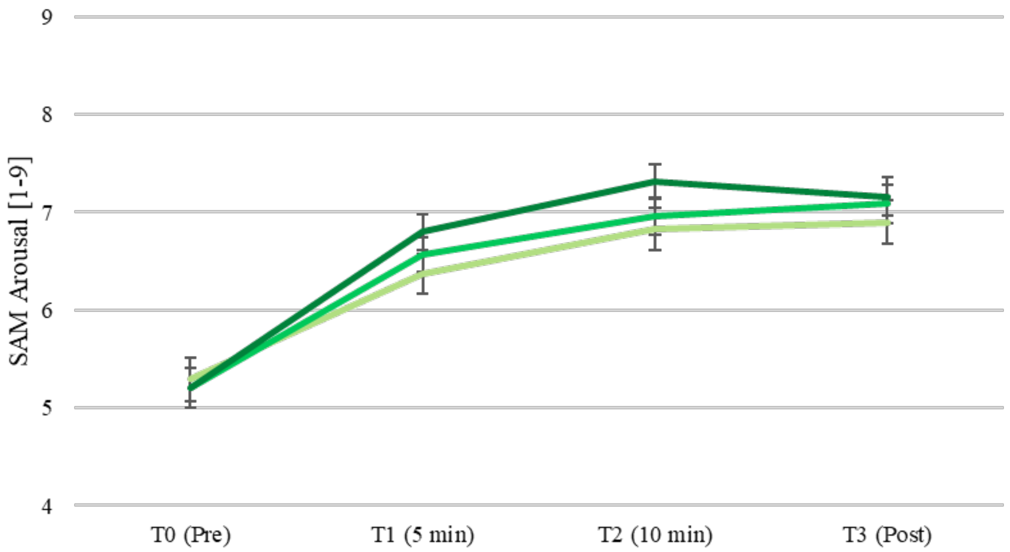
D5. Valence



	M (SE)	M (SE)	M (SE)	M (SE)
NO-FB	2.55 (0.19)	2.53 (0.20)	2.61 (0.20)	2.88 (0.18)
ST-FB	2.67 (0.19)	2.84 (0.18)	2.85 (0.19)	2.99 (0.18)
PO-FB	2.71 (0.19)	2.98 (0.17)	3.21 (0.18)	3.48 (0.17)

Note. NO-FB: No feedback. ST-FB: Standard acoustic environment. PO-FB: Standard acoustic environment and positive feedback. Error bars represent the standard error of the mean. Effect of time: $p < 0.001$, $\eta^2_p = 0.24$. Effect of feedback condition: $p = 0.010$; $\eta^2_p = 0.09$. Effect of time × feedback condition: $p = 0.241$; $\eta^2_p = 0.08$. Results of post-hoc comparisons for feedback effect (significant results bolded): **PO-FB vs. NO-FB: $p = 0.011$, $\eta^2_p = 0.08$**; **PO-FB vs. ST-FB: $p = 0.042$, $\eta^2_p = 0.04$**; NO-FB vs. ST-FB: $p = 0.542$, $\eta^2_p = 0.02$.

D6. Arousal



	T0 (Pre)	T1 (5 min)	T2 (10 min)	T3 (Post)
	M (*SE*)	*M* (*SE*)	*M* (*SE*)	*M* (*SE*)
NO-FB	5.29 (0.22)	6.37 (0.21)	6.83 (0.21)	6.90 (0.22)
ST-FB	5.21 (0.20)	6.57 (0.18)	6.96 (0.19)	7.09 (0.19)
PO-FB	5.20 (0.20)	6.80 (0.19)	7.31 (0.18)	7.16 (0.19)

Note. NO-FB: No feedback. ST-FB: Standard acoustic environment. PO-FB: Standard acoustic environment and positive feedback. Error bars represent the standard error of the mean. Effect of time: $p < 0.001$; $\eta^2_p = 0.61$. Effect of feedback condition: $p = 0.222$; $\eta^2_p = 0.03$. Effect of time × feedback condition: $p = 0.009$; $\eta^2_p = 0.16$. Results of post-hoc comparisons for time × feedback effect (significant results bolded): At T0: PO-FB vs. NO-FB: $p = 0.349$, $\eta^2_p = 0.01$; PO-FB vs. ST-FB: $p = 0.730$, $\eta^2_p = 0.00$; NO-FB vs. ST-FB: $p = 1.000$, $\eta^2_p = 0.00$. At T1: PO-FB vs. NO-FB: $p = 0.117$, $\eta^2_p = 0.01$; PO-FB vs. ST-FB: $p = 0.408$, $\eta^2_p = 0.00$; NO-FB vs. ST-FB: $p = 0.886$, $\eta^2_p = 0.00$. At T2: **PO-FB vs. NO-FB: $p = 0.047$, $\eta^2_p = 0.04$;** PO-FB vs. ST-FB: $p = 0.079$, $\eta^2_p = 0.03$; NO-FB vs. ST-FB: $p = 1.000$, $\eta^2_p = 0.00$. At T3: PO-FB vs. NO-FB: $p = 0.592$, $\eta^2_p = 0.01$; PO-FB vs. ST-FB: $p = 1.000$, $\eta^2_p = 0.00$; NO-FB vs. ST-FB: $p = 0.832$, $\eta^2_p = 0.00$.